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INTEGRATING UNMANNED AERIAL VEHICLES INTO SURVEILLANCE SYSTEMS IN COMPLEX MARITIME ENVIRONMENTS

by

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13. ABSTRACT (maximum 200 words)

One of the most important missions all Navies have is to constantly and sufficiently monitor their area of responsibility. This task becomes more challenging when a surveillance system operates in a complex environment with high traffic of merchant and fishing vessels and the existence of many islands. Potential tactics that targets might use increase the difficulty of this task. Integrating Unmanned Aerial Vehicles (UAVs) into a surveillance system that consists of ground radars and surface ships might enhance the system's capabilities and mitigate its vulnerabilities. In this study, the extremely complex maritime environment of the Aegean Sea is modeled in the Map Aware Non Uniform Automata (MANA) agent-based simulation environment to explore the effectiveness of UAVs in those conditions. The results from almost 100,000 simulated Intelligence, Surveillance, and Reconnaissance missions are analyzed using descriptive statistics, ANOVA, stepwise regression, and partition trees. It was found that by integrating one or two UAVs into a traditional surveillance system, it becomes more efficient in the detection and persistent surveillance of enemies and neutral targets. The most important factors that affect the surveillance system's performance are the detection capabilities of its sensors, the communication accuracy, and the enemy's counter-detection capability. Thus, Greece and other countries with similar geographical characteristics should deploy UAVs in a maritime surveillance role.

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INTEGRATING UNMANNED AERIAL VEHICLES INTO SURVEILLANCE SYSTEMS IN COMPLEX MARITIME ENVIRONMENTS

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ABSTRACT

One of the most important missions all Navies have is to constantly and sufficiently monitor their area of responsibility. This task becomes more challenging when a surveillance system operates in a complex environment with high traffic of merchant and fishing vessels and the existence of many islands. Potential tactics that targets might use increase the difficulty of this task. Integrating Unmanned Aerial Vehicles (UAVs) into a surveillance system that consists of ground radars and surface ships might enhance the system's capabilities and mitigate its vulnerabilities. In this study, the extremely complex maritime environment of the Aegean Sea is modeled in the Map Aware Non Uniform Automata (MANA) agent-based simulation environment to explore the effectiveness of UAVs in those conditions. The results from almost 100,000 simulated Intelligence, Surveillance, and Reconnaissance missions are analyzed using descriptive statistics, ANOVA, stepwise regression, and partition trees. It was found that by integrating one or two UAVs into a traditional surveillance system, it becomes more efficient in the detection and persistent surveillance of enemies and neutral targets. The most important factors that affect the surveillance system's performance are the detection capabilities of its sensors, the communication accuracy, and the enemy's counter-detection capability. Thus, Greece and other countries with similar geographical characteristics should deploy UAVs in a maritime surveillance role.

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LIST OF ACRONYMS AND ABBREVIATIONS

AIS	Automatic Identification System
AOI	Area of Interest
AWACS	Airborne Warning and Control System
BAMS	Broad Area Maritime Surveillance
BDA	Battle Damage Assessment
COP	Common Operational Picture
DoD	Department of Defense
DOE	Design of Experiment
DTS	Discrete Time Simulation
EO/IR	Electro-Optical/Infrared
EU	European Union
FOV	Field of View
FRONTEX	from French: Frontières extérieures (legally: European Agency for the Management of Operational Cooperation at the External Borders of the Member States of the European Union)
GCS	Ground Control System
GHMD	Global Hawk Maritime Demonstration
HN	Hellenic Navy
IR	Infrared
ISR	Intelligence, Surveillance, and Reconnaissance
LH	Latin Hypercubes
MANA	Map-Aware Non-uniform Automata
MCCIS	Maritime Command and Control Information System
MDA	Maritime Domain Awareness
MOE	Measure of Effectiveness
MPA	Maritime Patrol Aircraft
NATO	North Atlantic Treaty Organization
NOLH	Nearly Orthogonal Latin Hypercubes
RADAR	Radio Detection and Ranging

RMP	Recognized Maritime Picture
SA	Situational Awareness
SAR	Search and Rescue
SEAD	Suppression of Enemy Air Defense
SEED	Simulation Experiments and Efficient Design
SSC	Surface Search and Control
STUAS	Small Tactical Unmanned Aerial System
ToT	Time on Task
UAS	Unmanned Aerial System
UAV	Unmanned Aerial Vehicle
VTUAS	Vertical Takeoff Unmanned Aerial System
VTUAV	Vertical Takeoff Unmanned Aerial Vehicles

THESIS DISCLAIMER

The reader is cautioned that the computer programs presented in this research may not have been exercised for all cases of interest. While every effort has been made within the time available to ensure that the programs are free of computational and logical errors, they cannot be considered validated. Any application of these programs without additional verification is at the risk of the user.

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EXECUTIVE SUMMARY

One of the most fundamental missions of the Hellenic Navy is surveillance of its territorial waters, as well as the waters in its region. This mission is undoubtedly of strategic importance taking into consideration the geographical region where Greece is located, at the intersection of three continents (Europe, Asia and Africa), as well as Greece's participation in the European Union (EU) and North Atlantic Treaty Organization (NATO).

Monitoring the Aegean Sea, the Eastern area of the Mediterranean Sea, is by default difficult because it demands cooperation among different sensors. These sensors might be ground radars, patrol ships, air force reports, and various electromagnetic or electronic detections. The complexity of the maritime environment increases the difficulty in the surveillance. The most distinctive geographical characteristic of the Aegean Sea is the number of islands located there. Despite its relatively narrow area, the Aegean Sea accommodates more than 3,000 islands, islets, and rocks. Furthermore, this sea is used by approximately 55,000 transiting merchant vessels on an annual basis.

The current maritime surveillance system in Greece, despite its cost and its demands on human resources and material, is highly vulnerable due to a number of factors. First of all, the weather conditions affect the current sensors in various ways. For example, high sea states may prevent small surface ships from patrolling. Moreover, low visibility does not allow the visual observers to locate targets at longer distances. Similarly, in rainy conditions radars are negatively affected, resulting in smaller detection ranges. Another limiting factor is location. "Blind sectors," the areas that are not covered by the ground radar systems, result from the way systems must be positioned. Finally, the adversary's tactics may diminish the detection range. Such tactics include two targets sailing very close to one another or vessels staying close to the shoreline.

Greece is facing a major challenge to cope with the large influx of mixed migratory flows (including irregular migrants, refugees, and asylum seekers) and the current economic crisis. According to EU, Greece has become the main entry point for irregular migratory flows into the European Union. In 2010, more than 132,000 third-country nationals were arrested in Greece, including 53,000 in the Greek-Turkish border regions. During the first ten months of 2012, over 70,000 arrests occurred, including about 32,000 at the border with Turkey. People came from 110 different countries, the majority from Asia and the Middle-East.

Conventional wisdom states that Unmanned Aerial Vehicles (UAVs) offer two main advantages over manned aircraft: they are considered more cost-effective, and they minimize the risk to a pilot's life. This study investigates the ways in which UAVs can be integrated into a traditional surveillance system that utilizes only ground radars and surface ships.

Using an agent-based simulation environment called Map-Aware Non-uniform Automata (MANA), two representative areas of the Aegean Sea are modeled for our research; the "Open Sea" model, where a ship has to sail for about 50 nautical miles without the "coverage" of nearby islands, and the "Many Islands" model, where several islands are very close to one another. The first represents a typical area of the Northern and Southern Aegean Sea and the second of the Central and Southeast Aegean Sea. These rare geographical conditions compose a challenging environment operationally.

In our simulation the Red Force consists of four surface vessels. These vessels attempt to transport illegal immigrants into Blue's area of responsibility. To increase the possibility of going undetected, they keep close to nearby merchant vessels that have approximately the same course with them ("Open Sea" model), or they try to take advantage of islands by sailing close to the shoreline during their route ("Many Islands" model).

Following the base model, a Nearly Orthogonal Latin Hypercube (NOLH) is created to efficiently explore the effect of 21 variables on the percentage of

time the targets are positively identified. These 21 factors were chosen based on opinions of subject matter experts, as well as the author's experience. In addition to the 21 independent variables that are explicitly varied in the Design of Experiment (DOE), there are an additional 52 variables that depend on one of the aforementioned factors. These variables describe the sensors' capabilities.

The simulation runs show that integrating one or two UAVs into a traditional surveillance system makes it more efficient in the detection and persistent surveillance of enemies and neutral targets. This conclusion applies to all the areas of the Aegean Sea, both the Northern and Southern Aegean Sea (modeled by the "Open Sea" model) and the Central and Southeast (modeled by the "Many Islands" model).

In all the cases we studied, we consistently found that a traditional system with only surface ships and ground radars performs worse than a system that uses UAVs. Additionally, we explored a "futuristic" scenario in which only two UAVs support the ground radars, without the use of surface ships (no Blue ships scenario). The results show that we can obtain similar results with the case where we deploy one UAV and two surface ships in support of the ground radars (1-UAV scenario). This conclusion indicates that decision makers should review the surveillance policy. They can shift from the cost-ineffective use of surface ships towards the use of UAVs to better monitor maritime areas. This solution might be more beneficial in adverse weather conditions or when there is a lack of operational surface units.

This study also demonstrates that the potential tactics the enemy might use to avoid detection cannot mislead UAVs. Whether the enemies try to take advantage of nearby merchant vessels and sail close to them to transit long distances, or to use the shorelines of numerous islands as coverage, a surveillance system that deploys UAVs is able to present significantly better performance than a system that uses only ground radars and surface ships.

Furthermore, this thesis shows that the area from which a UAV is launched affects the performance of the whole surveillance system. As it is easily understood, the more contacts that exist close to the launch site, the more the UAV contributes to the surveillance system. That is, if the launch site is close to areas with high traffic, the UAV will have more opportunities to locate the targets. Additionally, the targets will be identified earlier. Therefore, it is extremely important to define the best launch site for the UAVs. From the literature review, we found that UAVs can be launched either from ground-based sites or appropriately equipped surface ships. Both solutions must be examined for strengths and vulnerabilities.

This study also shows that UAVs can mitigate a vulnerability that ground radar systems inherently have: the inability for fixed radars to cover their "blind sectors," which result from the way systems must be positioned. Because monitoring the whole range of the Area of Interest (AOI) with ground radars is not practical (it would require twice as many sensors), the existing radars are placed in areas with the most traffic. As a consequence, these systems are not always stationed at the highest point of an island, which results in a limited field of view. Additionally, taking into account that radar technology is subject to technical restrictions, the detecting capabilities are further narrowed. UAVs can easily cover those areas providing information about existing targets.

Finally, this thesis found the important factors that contribute to the maritime surveillance system. The two models that modeled corresponding environments in terms of transiting merchant vessels, the existence of nearby islands and the enemy's tactics were studied separately, but most of the input variables appear in both of them.

- The detection range of all the sensors that are part of the surveillance system seems to have the most significant positive effect on the percentage of time the targets are classified. The partition tree for the "Open Sea" model highlights the importance of having the radars, the UAV, and the ships' detection ranges larger than 22, 19 and 16 km, respectively.

- Communication accuracy of the Operational Centre has a significant positive effect on the system's performance. The partition tree for the "Many Islands" model suggests a value of at least 78 percent to better monitor the area of interest. It worth noticing that the Operational Centre is crucial in the communication network that we established because its role is to gather the information from each one of the sensors and send them to the patrolling units.

- Enemy's stealth is a factor that has a significant negative impact on the percentage of time a target is classified. Enemy's stealth is presented in both the scenarios we studied where a target used a specific tactic to avoid being detected by the surveillance system. In reality, this factor describes the enemy's attempt to avoid the visual, infrared (IR), and radar contact using various methods.

- The number of merchant vessels and their speed has a negative effect on the surveillance system's performance only in the case where the enemy tries to use them as a "Trojan Horse" to transit long distances. In environments where there is high traffic, either from merchant or fishing vessels, but the enemy does not try to take advantage of it, it seems that the surveillance system is not affected.

- Average Times between Detections of our own sensors are additional important factors in terms of the surveillance system's detection capability. All of them positively affect the percentage of time the targets are classified, regardless of the operational environment in which the system operates.

- The enemy's speed is a factor that has a significant negative effect on the percentage of time the targets are classified. This factor emerged only in the "Open Sea" model where the target has to transit long distances being "exposed" to the adversary's surveillance system. This is operationally reasonable because when a target sails very close to the shoreline to avoid the detection, it cannot maintain a high speed due to navigation dangers.

- UAV speed has a positive effect on the system's performance only in the case where it has to cover large areas. This study showed that when the UAV had to cover areas with a large number of islands, its speed was not important.

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always struggle in their lives to see their child accomplish his goals. They have been always proud of me, and I am proud of them, too.

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I. INTRODUCTION

A. GENERAL FRAMEWORK

1. The Role of Hellenic Navy in Surveillance

The geographical region where Greece is located, at the intersection of three continents (Europe, Asia and Africa), is undoubtedly of strategic importance in surveillance (Figure 1). Traditionally, Greece's foreign policy focuses on two major priorities. The first priority is to employ foreign policy as "an operational instrument for solving problems both in the region, where Greece is located, as well as in the wider international system."

Figure 1.   Strategic importance of Greece's location (From Wikimedia.org).

The second priority is "to contribute actively to promoting peace, stability and cooperative patterns of behavior in the region of Southeastern Europe and most specifically in the Balkans, and the area of the Eastern Mediterranean" (Kranidiotis, 1998).

Working in this context, the Hellenic (Greek) Navy's mission includes "contribution to the deterrence against any potential aggressor and the unabated support to Allied, European Union and other international efforts so as to fulfill Greece's commitment as a dedicated contributor to North Atlantic Treaty Organization, European Union, and United Nations, maintaining readiness to effectively contribute to defense and security of the Nation" (Karamalikis, 2008, p. 31).

One of the most fundamental missions of the Hellenic Navy is surveillance of the territorial waters, as well as the national waters that are close to them. This mission is difficult because it demands cooperation between different sensors. These sensors might be ground radars, patrol ships, air force reports, and various electromagnetic or electronic detections. A serious parameter for the Hellenic Navy is the degree of cooperation with the Coast Guard and/or the sharing of information with international stakeholders.

The importance of this mission is reinforced by Greece's participation in the European Union (EU). In the context of EU enlargement, Europe's maritime borders have now expanded with Europe's coastline to contain 85 percent of the EU's international borders. From the EU's perspective, this expansion will require increased surveillance to tackle problems such as illegal immigration and other illicit activities linked to organized crime, such as drug smuggling, human trafficking and the trafficking of illicit materials such as WMD and explosives. Effective monitoring of EU external borders requires increased cooperation between relevant stakeholders, such as coast guard organizations and law enforcement agencies, in maritime surveillance.

The Mediterranean Basin is a strategically important region for the EU, and it is necessary to construct a strong economic area capable of contributing to the Union's regional balance by assuring peace, stability and prosperity. The Barcelona Initiative was launched with these objectives in mind and is now a central element of the EU-Mediterranean Policy. Furthermore, the Hellenic Navy aims to be vigilant in detecting all threats that might cause instability in the area

in which it operates. Those threats, like terrorism, organized crime, and political or economic crises must always be taken into serious consideration at the campaign level, as well as at the operational level (Kyriazis, 2004, pp. 64-66, 68, 71-73).

Traditionally, the Navy handles the surveillance mission with multiple assets under a broad mission called Surface Search and Control (SSC). At sea, surface detections are often made by medium-range ground radars scattered on numerous islands which provide optimal coverage with respect to sensor capabilities and operational priorities. Additionally, a large number of surface ships are assigned to patrol comparatively small sectors in order to contribute to either the detection or the identification task.

Besides the Navy assets, ground-based or surface, there are additional means from other military branches or organizations that provide useful information to the Hellenic Navy which has the coordinating role. A detailed presentation of all the stakeholders who participate in the current surveillance system is provided in Chapter II.

Realistically, not all the assets are available at all times. All the information received from these assets is used to form and maintain the Recognized Maritime Picture (RMP). The RMP is "about maintaining an unambiguous and timely database of the position and identification of all tracks, both warship and merchant, and being able to distinguish good or cleared ships from the adversary, unchallenged, suspect, or blockade running ships" (Germain, 1997). The RMP assists the commanders in obtaining the intelligence needed to use their assets more effectively and consequently achieve their mission.

2.   Complexity of the Maritime Environment

The Aegean Sea, which is the Eastern maritime frontier of European Union, is the area in which the Hellenic Navy mostly operates. The most distinctive geographical characteristic of Aegean Sea is undoubtedly the number of islands located there. Despite its relatively narrow area, the Aegean Sea

accommodates more than 3,000 islands, islets and rocks (Acer, 2003). Furthermore, this sea is used by transiting merchant vessels sailing towards the Black Sea (Northeast), Red Sea (South) and Middle East (East). It is estimated that approximately 55,000 merchant vessels cross this area annually (Camci, Eldemir, Uysal, & Ustun, 2009, pp. 424–429). If we take into consideration the large number of fishing vessels (both Greek and Turkish) and sailing boats, especially during the summer, one can conclude how difficult it is to monitor this Area of Interest (AOI). This task is further complicated when a "target" uses unusual tactics to mislead the assigned surveillance sensors.

3.   Vulnerabilities of the Current Surveillance System

The current maritime surveillance system in Greece, despite its cost and its demands on human resources and material, is highly vulnerable due to a number of factors. First of all, the weather conditions affect the current sensors in various ways. For example, high sea state prevents small surface ships from patrolling. Moreover, low visibility does not allow the visual observers to locate targets at large distances. Similarly, in rainy conditions radars are negatively affected, resulting in smaller detection ranges (Schneider & Williams, 1977, pp. 11–29).

Another limiting factor is location. "Blind sectors," the areas that are not covered by the ground radar systems, result from the way systems must be positioned. Since monitoring the whole range of the AOI with ground radars is not practical (it would require twice as many sensors), the existing radars are placed in areas with the most traffic. As a consequence, these systems are not always stationed at the highest point of an island, which results in a limited field of view. Additionally, taking into account that radar technology is subject to technical restrictions, the detecting capabilities are further narrowed.

Finally, the adversary's tactics may diminish the detection range. Such tactics include two targets sailing very close to one another or close to the

shoreline. In such cases the resolution of the radar might not be adequate to distinguish the targets (Wehner, 1994; Hutchinson, 2003).

Furthermore, these limiting factors are multiplied by the complex environment in which maritime activities occur. This complexity provides the targets involved in illegal activities or adversary warships that are enemies of the North Atlantic Treaty Organization (NATO), the EU or Greece, with potential ways to avoid detection.

As mentioned above, an extremely large number of people and operating subsystems (units) have to collaborate in the current surveillance system. The existing system involves people from different branches (Navy, Army, Air Force) with different backgrounds (personnel coming from conscription in contrast to voluntary military members), as well as from different countries and security organizations. This diversity may be the biggest vulnerability of the surveillance system, even bigger than human error or the deficiencies of the existing means. Any new system should take into account the leveraging of differences among participants to produce innovative, synergistic solutions and balancing of divergent stakeholder concerns (Hardy, Lawrence, & Grant, 2005).

Adding to the challenge, although the cooperation with the international organizations (NATO, EU) is exceptional, this cooperation cannot be exclusively relied upon, because the majority of the RMP concerning the Aegean Sea actually is drawn from the Greek reports. In other words, the majority of the information flows from the Hellenic Navy to the other stakeholders rather than the other way around. That reinforces Greece's responsibility to its allies for providing near-to-real time and accurate Situational Awareness (SA) in the AOI.

Furthermore, the participation of the EU's units in patrolling the area of operations definitely assists in the task of surveillance. Even so, the inherent problems of that system, such as vulnerabilities due to weather conditions, fatigue of the crew, restriction of the detection devices (e.g., radar, night vision goggles) remain a challenge to the Greek Navy. Additionally, EU assistance

holds only for a period of time throughout the year (two to three months annually).

Finally, the financial crisis in Greece resulted in a significant budget cut in the Ministry of Defense. As a consequence, systems that are economical and, at the same time, highly effective must be adopted throughout all the sectors, including the Hellenic Navy. Although the exact cost for the surveillance of the Aegean Sea is unavailable and difficult to estimate (because it involves a tremendous number of people and manned devices or units), the cost certainly is significant. Therefore, budget cuts to surveillance of the Aegean Sea prompt the Greek Navy to derive more cost efficient methods of surveillance.

B.   PROBLEM STATEMENT

The greatest challenge for the current surveillance system, which does not involve Unmanned Aerial Vehicles (UAVs), is to detect comparatively small targets (with small Radar Cross-Section). As stated earlier, a common technique of small targets is to stay close to the shoreline. Current radar resolution cannot distinguish the presence of a small ship so close to the shoreline. This problem arises when hostile, relatively small warships (like fast attack boats) or other small boats, which might participate in illegal transactions (e.g., human trafficking, smuggling, etc.), try to take advantage of this situation and avoid being detected by the Greek Naval surveillance system.

A second problem arises when small hostile warships are assigned to transit an "open sea," which is considered an area with no island for about 50 nautical miles. In the open sea, small ships are extremely exposed and can readily be detected by their adversary's assets (e.g., air assets, frigates, ground radars, etc.). Additionally, small ships are unable to protect themselves because they lack anti-air weapons and self-defense systems or missiles. Thus, these small warships commonly take advantage of the presence of large merchant vessels/tankers and remain as close to them as they can to avoid detection. The nature of the Aegean Sea favors this practice.

C.   PURPOSE OF THIS STUDY

The purpose of this study is not to build a completely new surveillance system, but to introduce the potential benefits of using new technologies/sensors which complement the current system. For this reason, we will try to explore the ways in which UAVs can be engaged in this process. This application will be an innovation for the countries of the East Mediterranean that currently do not use UAVs in surveillance of maritime areas.

The primary reason that we look into this solution is because UAVs are increasingly utilized by developed countries in the global operational environment today (Frederick, 2006), and this trend is expected continue in the years ahead. Additionally, the use of UAVs is believed to mitigate the inherent vulnerabilities of the current surveillance system mentioned earlier, as well as reduce the overall cost of surveillance. Taking the U.S. Navy as an example, it intends to increase the number of UAVs in service while at the same time reduce the number of operators (Liu, Wasson, & Vincenzi, 2009, pp. 795–810). Another example is the replacement of helicopters by Vertical Takeoff Unmanned Aerial Vehicles (VTUAVs) in the U.S. Navy's planned 56-ship fleet of Littoral Combat Ships (Burgess, 2004, pp. 24–25).

Undoubtedly, the global investment in unmanned systems accelerated following 9/11 and UAV successes in Iraq and Afghanistan. During the decade of 2005–2015, the global market for UAVs (including all air vehicles, ground control equipment and payloads) is an estimated $16 billion. The U.S. Department of Defense (DoD) annual profile for Unmanned Aerial Systems (UAS) is depicted in Figure 2. Europe could spend over 1 billion euros on procurement and possibly more on research and development (Dickerson, 2007, pp. 114–116).

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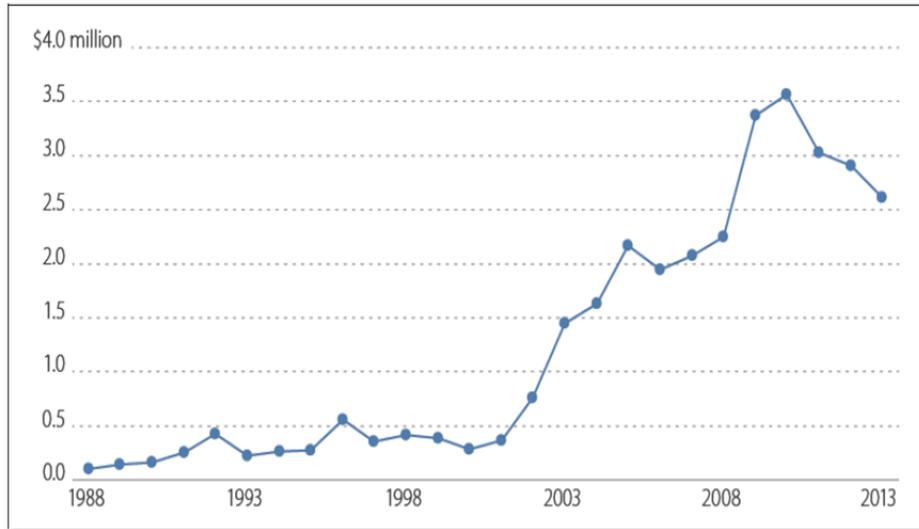
Figure 2.   U.S. DoD annual profile for unmanned aerial systems (From U.S. Library of Congress, 2012).

There have been numerous studies that demonstrate the effectiveness of UAVs in border security (Yildiz, 2007) and homeland security (Myers, 2007; Weiger, 2007). An additional fact that proves the need for aerial means in the AOI comes from the NATO contribution to Greece with Airborne Warning and Control Systems (AWACS) aircraft during the 2004 Olympic Games (Graham, 2004). At that time, although there was a fleet of eight surface ships patrolling the Aegean Sea (in national and international waters) it was considered necessary to have in addition one air asset with advanced capabilities. In comparison to that time, perhaps the current need for constant coverage of the AOI is not so obvious, and the assets assigned are definitely fewer than in the past. For all these reasons we will try to answer similar questions from the perspective of operating in a complex maritime environment.

This study investigates whether a surveillance system with the use of UAVs performs better than a traditional system. In other words, we explore whether UAVs are capable of mitigating all or part of the vulnerabilities of the current sensors (e.g., ground radars, patrol ships, etc.). Additionally, we explore

what factors should be considered in designing more effective surveillance systems that meet the needs of the geographical area in which they will operate.

D. SCOPE OF THESIS

This thesis focuses on reinforcing the surveillance system in complex maritime environments where high maritime traffic is met and where targets may take advantage of adjacent islands or transiting merchant vessels to avoid detection. Furthermore, it is assumed that the current surveillance system does not involve UAV capabilities, but the benefit of UAV capabilities will lead to their implementation with current sensors in the future.

The scope of this study is not to build a new surveillance system from the beginning, but to suggest new elements that could easily be incorporated into the existing system. These elements will fill in the gaps and mitigate the vulnerabilities that have already been recognized in the current model and will form a solution that meets the surveillance objectives being posed.

This study investigates the extent to which the Hellenic Navy will benefit from integrating UAVs into the existing surveillance system in its AOI. For this reason, the sensors that currently are involved in this task are studied in compliance with the complex maritime environment in which they operate, like the Aegean Sea.

E. RESEARCH QUESTION AND CORRESPONDING HYPOTHESES

1. Primary Research Question

Does the use of UAVs in a surveillance role mitigate the limitations of the current surveillance system to detect targets in complex maritime environments, assuming that the target's tactic is to approach transiting merchant vessels or take advantage of nearby shorelines?

Hypotheses for the Primary Research Question:

- H_0: There is no difference in the surveillance system's performance whether it uses UAVs or not assuming that the target's tactic is to approach transiting merchant vessels or to take advantage of nearby shorelines.

- H_A: A surveillance system with UAVs performs better than one without UAVs assuming that the target's tactic is to approach transiting merchant vessels or to take advantage of nearby shorelines.

2.   Exploratory Research Questions

What are the important factors that contribute to maritime surveillance when UAVs are used?

- Is the number of transiting neutral vessels an important factor?
- Is the length of the shoreline an important factor for the surveillance system's performance?

F.   OVERVIEW OF METHODOLOGY

To explore the problem posed, we use an agent-based simulation environment called Map-Aware Non-uniform Automata (MANA). In this simulation tool we set up a model that represents the current surveillance system. This model is compared, applying appropriate statistical techniques, with another which uses UAVs in addition to the sensors the previous model used.

The input data are assembled by reviewing technical data, manufacturer supplied information, article reviews, and subject matter expert interviews. Since the input values are not always fixed or known, a range of them is used. In this way, the uncertainties of the inputs are mitigated, and some of the stochastic effects of the warfare are captured (Abel, 2009). A Nearly Orthogonal Latin Hypercube (NOLH) design is used to create a pattern of different starting conditions. For each condition, a simulation is run for a sufficient number of replications to estimate the variability in the output. Exploratory data analysis techniques are used to characterize the impact of surveillance sensors and tactics on the overall performance of the surveillance system.

Our simulation model captures the following attributes:

- Enemy targets try to take advantage of the presence of transiting merchant vessels and the nearby shoreline at all times.

- All the other sensors, besides the UAVs, have the same capabilities either with or without the presence of UAV.

- The assigned UAV covers those areas that the ground radars are incapable of covering.

The assumptions of the models we create are presented in detail in Chapter III.

G. BENEFITS OF THE STUDY

This study will benefit the decision makers, either officers or politicians, who need to understand how UAVs might be force multipliers. In other words, our research will test the value of UAVs in monitoring complex maritime environments and provide the initial guidelines for the use of UAVs in the maritime domain. Additionally, results from this study will assist decision makers in forming the future policy and/or tactics, techniques and procedures for small friendly warships to counteract UAVs.

We are expecting that the results of this study will be applied in similar surveillance situations in different domains. A potential area of exploration could be the monitoring of maritime traffic in the vicinity of ports. Another area could be in border security when combining ground, aerial and maritime sensors. This solution could be investigated for situations where potential illegal activities might happen using various techniques to mislead the detection sensors both on the ground and in the sea or rivers.

H. THESIS FLOW

Chapter II offers a description of the AOI and of the concept of surveillance operations. It continues with a discussion of the illegal activities that may be encountered. Information about the agencies and units involved in the

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current surveillance system in Greece is also provided. Finally, the airborne platforms currently in use by the U.S. Navy that might be fitted in the case studied are described.

Chapter III begins with an overview of the modeling tool, MANA, and the scenario description. Moreover, it provides a detailed description of the model and the way it is built.

Chapter IV presents the design of experiment, as well as a description of the variables used in the analysis.

Chapter V starts with an overview of the analytical techniques being used. It continues with the data obtained from the simulation, and it closes with the analysis section using appropriate statistical techniques.

Chapter VI concludes this thesis, summarizing the results, giving a thorough discussion of the analysis and offering follow-on problems and recommendations. The complete analytical work is contained in the Appendices.

II. BACKGROUND

A. AREA OF INTEREST

Greece is an EU Member State in South-Eastern Europe and is mostly surrounded by sea. It has a coastline on the Ionian Sea in the west, the Adriatic Sea in the northwest, the Aegean Sea in the east and the Eastern Mediterranean in the south and southeast. Its coastline length is an estimated 17,400 km. In Greece's territory there exist about 10,000 islands and islets making up around 70 percent of country's coastline. Greece has a 6 nm territorial sea, but has repeatedly declared that "it reserves its legitimate right under international law to establish a 12 nm territorial sea at a time deemed appropriate" (European Commission Study, 2013).

Greece's most significant maritime activities are maritime transport, marine and coastal tourism, and fisheries. Greece has the largest merchant fleet in the EU and one of the largest merchant fleets in the world. The country is surrounded by a rather large number of important shipping lanes (Figure 3) and has 20 ports that process more than one million tons of cargo per year (European Commission Study, 2013).
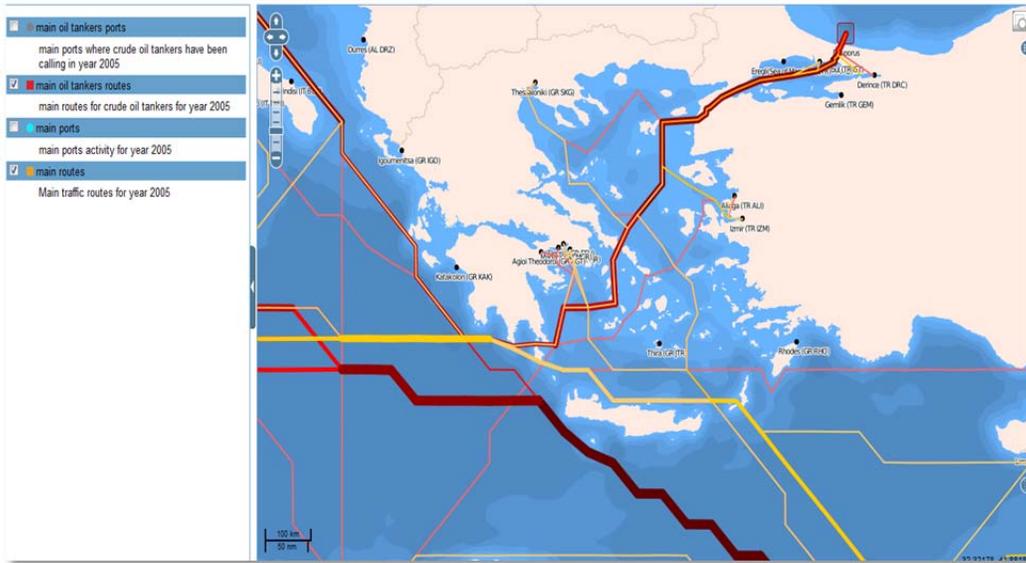
Figure 3.   Major shipping routes near Greece (From Safemed Project, www.safemedgis.org).

The traffic in the Greek seas is enhanced by commercial shipping among the ports, recreational boating, as well as ferry transportation. Additionally, Greece is a popular tourist destination (ranked 15th worldwide). Tourism is extremely important for the Greek economy because it contributes more than 18 percent to the annual Gross National Product. A large number of cruise ships sail the Greek waters, especially during summer.

Given Greece's unique geographical features and, in particular, its extensive insular territory, the country's territorial and social cohesion depends directly on the existence of frequent and reliable coastal shipping services (serving 94 islands, 144 ports and around 36 million passengers per year) (European Commission Study, 2013). More information about maritime transport can be found in Table 1.

Table 1.   Information about maritime transport (From European Commission Study, 2013).

– 3 996 ships in controlled fleet (≥1 000 GT, '09)
 	
– 969 ships under Greek flag (≥1 000 GT, '09)
 	
– Ferry passengers (cabotage '09): 64 648 474
 	
– Largest merchant fleet in EU and in the world:
 	
   o 23.48% of EU fleet in gt ('08)
 	
   o 13 % of the world's gross tonnage (Greek-owned fleet, '09)
	– Important container ports (container throughput in TEU, '07): Piraeus: 1 373 000; Thessaloniki: 447 000
	
	– Important cargo ports (metric tonnes, '07): Piraeus: 20 122 000; Thessaloniki: 8 466 000
	
	– Seaborne passenger transport between ports ('07): 45 858 000

This study focuses only on the Aegean Sea area because, as demonstrated above, it is more important than the other seas from the perspective of shipping routes, number of islands and maritime transport. In addition, this area is more vulnerable to illegal activities, as the next section describes.

B.   PROTECTING NATIONAL SECURITY

Greece is facing a major challenge to cope with both the large influx of mixed migratory flows, including irregular migrants, refugees and asylum seekers, and the current economic crisis. PACE, the Council of Europe's Parliamentary Assembly, adopted Resolution 1918 in 2013 calling for "firm and urgent measures [to] tackle the mounting pressure and tension over asylum and irregular migration into Greece, Turkey and other Mediterranean countries" (European Council, 2013). According to this Resolution, Greece has become the main entry point for irregular migratory flows into the European Union, while Turkey has become the main country of transit.

According to statistics provided by the United Nations High Commissioner for Refugees, in 2010 more than 132,000 third-country nationals were arrested in

Greece, including 53,000 in the Greek-Turkish border regions. During the first ten months of 2012, over 70,000 arrests occurred, including about 32,000 at the borders of Turkey. People came from 110 different countries, the majority from Asia and the Middle-East. The irregular migration routes in the Mediterranean Sea, based on 2012 data, are shown in Figure 4.
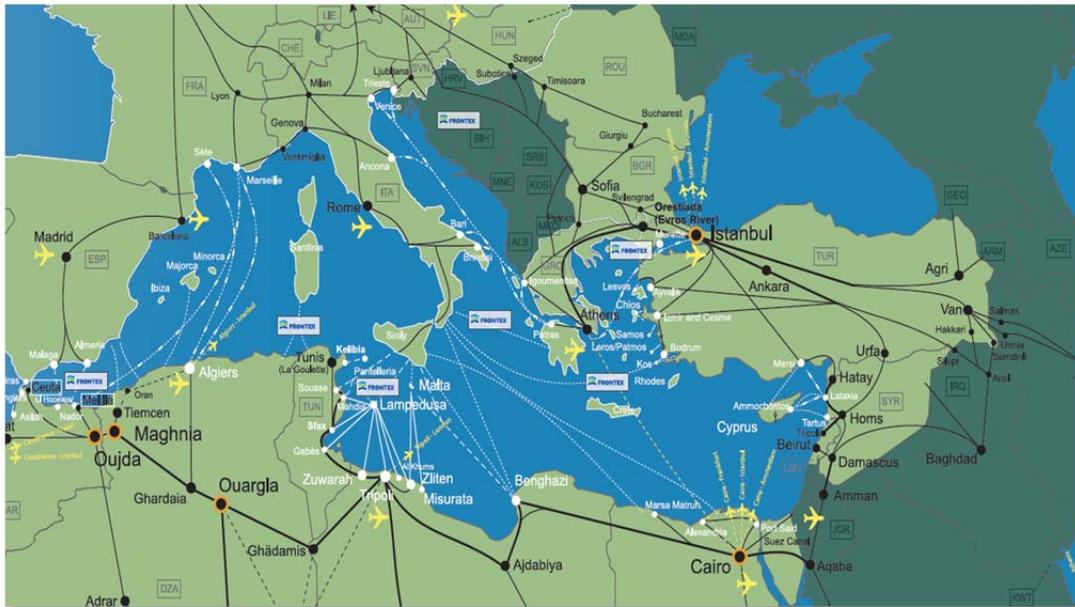
Figure 4.   2012 Map of irregular migration routes in Mediterranean Sea (From Interactive map on migration, http://www.imap-migration.org).

The problem has been traditionally more severe in the Eastern Mediterranean than in other regions, and this fact increases the responsibility of the adjacent countries to be more effective in monitoring their area of interest. The detection of illegal border-crossings in the Mediterranean Sea is shown in Figure 5. Although the situation on the Western route is not alarming, on the Eastern route detections have followed a remarkably seasonal pattern over the last two years with a constantly higher degree of illegal activity. In the second quarter of 2012, there were 14,125 detections of illegal border-crossing on the Eastern Mediterranean route, an increase of 27 percent compared to the same period in 2011. Concerning the Central Mediterranean route, we notice an

increase of detections of illegal border-crossings during 2011 due to the turbulent sociopolitical developments in North Africa known as the Arab Spring (FRONTEX, 2012).
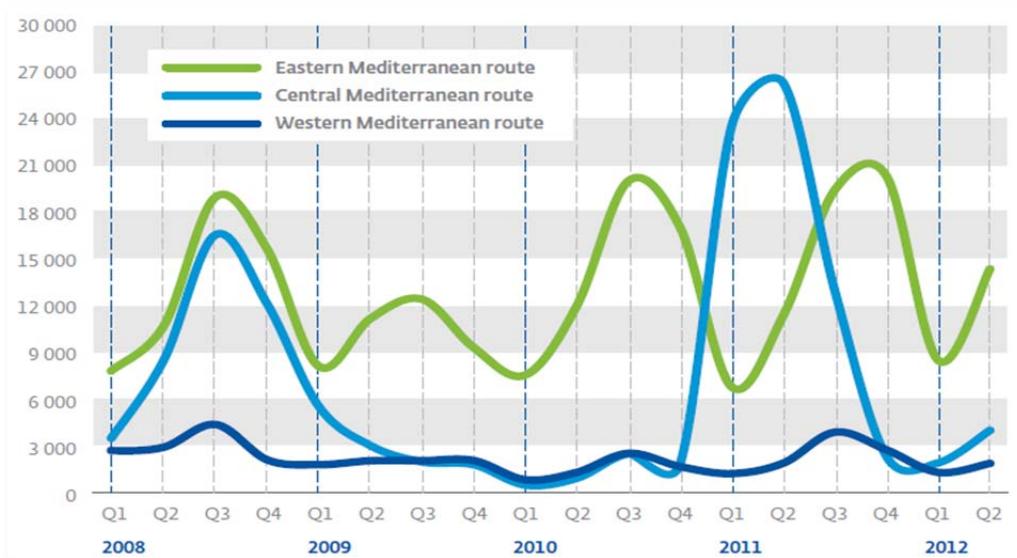
Figure 5.   Detections of illegal border-crossing between BCPs by main irregular migration routes (From FRONTEX, 2012).

Most migrants and asylum seekers use the Greek area as an intermediate step towards Europe. Many of them cannot exit the country due to border checks and arrests, and this restriction is one reason many of them return to their country of origin. The serious economic crisis of Greece aggravates the situation and negatively affects the efforts of the Greek authorities to respond to the large influx adequately (Strik, 2013).

The Greek Government has taken a number of measures to address the problem involving the land borders between Greece and Turkey, and these efforts have resulted in a tremendous decrease of irregular land border crossing. However, this fact impelled illegal migrants to use of sea routes between the two countries. During the last months, many reports show that migrants have been arriving on Greek islands of the Central and South Aegean Sea. Between August and December 2012, 3,280 persons were arrested after crossing the Greek-

Turkish sea border as compared to 65 persons in the first seven months of 2012. Moreover, an increase of deaths at sea has been confirmed. In September 2012, 60 people perished when their boat sank off the coast in Izmir, whereas on 15 December 2012, 20 bodies were found at sea off the coast of Lesvos (Reuters, 2012).

Not all of these migrants are individuals seeking asylum. Many cases of irregular border-crossing have involved human trafficking. In addition, smugglers might also be involved in cases of drugs and weapons trafficking, especially after the serious instability in the area since 2012, caused by the political problems in Syria. Surveillance capabilities should be enhanced not only to curtail these illegal activities but also to improve the legal fishery enforcement and the reaction time in Search-and-Rescue (SAR) operations.

C.   CONCEPT OF OPERATIONS

As stated in the previous chapter, there are a lot of different sensors that contribute to the RMP which is defined as "a composite picture of activity of a maritime area of interest for a given time" (Dore et al., 2002). To build a coherent RMP, a large number of civilian, military, and allied sensor systems must collaborate in a systematic way to gather as much information as is possible about the activities of the targets existing in the AOI. This information will be used by the decision makers at the operational and tactical level to plan and assign their assets accordingly.

The RMP helps to provide commanders with a Common Operational Picture (COP). The Joint Publication (JP) 3-0 defines the COP as "a single identical display of relevant information shared by more than one command that facilitates collaborative planning and assists all echelons to achieve situational awareness." In other words, RMP assists the commanders in obtaining the intelligence needed to use their assets more effectively and, consequently, achieve their mission. The purpose of the COP is to provide real-time information

on Blue, Red, and White forces (friendly, enemy, and neutral vessels) operating in the maritime domain.

Finally, the goal is to improve the Maritime Domain Awareness (MDA), which is defined in the JP 3-32 as the "effective understanding of anything associated with the maritime domain that could impact the security, safety, economy, or environment of a nation." To achieve complete MDA, all mission or functional areas of the components and agencies tasked must be incorporated into a common architecture that provides each with the ability to share near real-time information, synthesize inputs from multiple sources, and quickly analyze the data to affect improved decision making before the opportunity to investigate and act on identified threats is lost.

To achieve the desired detection of enemy combatants, the intelligence community utilizes an assortment of Intelligence, Surveillance, and Reconnaissance (ISR) sensors. According to JP 1-02, ISR is "an activity that synchronizes and integrates the planning and operation of sensors and assets, as well as the processing, exploitation, and dissemination of information in direct support of current and future operations." The JP 1-02 further defines the three ISR components individually:

- Intelligence—the product resulting from the collection, processing, integration, evaluation, analysis, and interpretation of available information concerning foreign nations, hostile or potentially hostile forces or elements, or areas of actual or potential operations.

- Surveillance—the systematic observation of aerospace, surface, or subsurface areas, places, persons, or things, by visual, aural, electronic, photographic, or other means.

- Reconnaissance—a mission undertaken to obtain, by visual observation or other detection methods, information about the activities and resources of an enemy or adversary.

Intelligence is broader term, while surveillance refers to systematic and constant observation of an area or a target, and reconnaissance refers to activities performed to obtain all the information needed about a detected contact (Brown & Schulz, 2009).

D.   AGENCIES INVOLVED IN CURRENT SURVEILLANCE SYSTEM

In this section, the agencies that currently participate in the Surveillance System of the Aegean Sea are briefly presented. The Surveillance System of the Aegean Sea consists of sensors belonging to different organizations. Because of the number of organizations and sensors involved, it is challenging to achieve completely accurate and timely information. The stakeholders that currently contribute to the National Surveillance System include the following:

1.   Hellenic Navy

Hellenic Navy (HN) is the main surveillance authority in the Maritime Greek territory. HN deploys its units taking into consideration the information from the other users (discussed later) and the Operational Plan the leaders draw. The ships (including frigates, fast patrol boats and submarines) are equipped with the newest devices with impressive capabilities. Although various types of ships might be involved in ISR Operations, a typical asset is the Gun Boat Osprey HSY 56A (Figure 6).

Figure 6.   HS AITTITOS (P- 268) (From Hellenic Navy, www.hellenicnavy.gr).

The navigation radar, the tracking radar and the infrared cameras provide advanced detection capabilities, while the radar's increased range capability is an advantage when there is need for covering large areas. The combination of its small draft with its relatively large displacement makes this gun boat capable of operating in shallow waters and in adverse weather conditions. The drawback is the Osprey's weakness in achieving high speed (>35 kn), which makes it incapable of pursuing fast targets. The general characteristics of this type of ship are depicted in Table 2.

Table 2.   General characteristics of HS MACHITIS (Type Osprey HSY 56A).

Length Overall	56.5 m
Beam (max.)	10 m
Draft	3.6 m
Displacement	575 tons
Speed	22 knots
Range	2,000 miles
Engines	2 Wartsila Diesel 16 V 25 2 X 5000 HP
Weapons	1 OTOMELARA 3" (76mm)/62 1 OTOBREDA 40mm/70 2 RHEIMENTALL 20mm 1 STINGER
Devices/Systems	LIROD MK 2 / TV CAMERA (FC) MIRADOR TVT-IRT Camera, Laser Firing Mode VARIANT Air-Surface Radar BridgeMaster E (Decca) NAVRAD RL80C MARPA (Raytheon) NAVRAD ESM / DR 3000 SLW TACTICOS (SMCS) / LINK 11

Additionally, the HN controls a number of ground radars located on several islands in Central and Eastern Aegean Sea, operated by military personnel. These radars collaborate with other sensors (i.e., radars, warships, merchant ships, etc.) in the adjacent areas to create the RMP. Although they achieve increased detection ranges, these radar systems do not have a 360-

degree Field of View (FOV) due to various physical obstacles (i.e., higher hills, mountains) resulting in the creation of "blind sectors." The ground radar system's location is chosen taking into consideration a number of factors, such as what area is more important to cover, what elevation provides higher detection range, what locations are capable of accommodating these stations and others.

Additionally, until recently, the HN operated a fleet of Maritime Patrol Aircraft (MPA) Orion P-3B, but due to economic deficiencies, they are not currently active. The MPA's missions were mostly in surveillance and anti-submarine warfare. These units were capable of flying at 9,000m, and their operational endurance was about 10 hours.

The HN also has the responsibility of exchanging information with numerous International stakeholders (NATO, Partnership for Peace countries and the EU) as will be explained later in this chapter.

2.   Hellenic Coast Guard

The Hellenic Coast Guard is a paramilitary organization that can support the Hellenic Navy in wartime, but it resides under the control of the Ministry of Merchant Marine and Aegean Sea in times of peace. The force has 158 patrol craft of various types and four light aircraft. The Coast Guard patrols all Greek harbors, coastlines, and territorial waters, monitoring anti-pollution measures and controlling merchant shipping. The Hellenic Coast Guard has permanently deployed small patrol ships in the major islands of the Central and Eastern Aegean Sea, and their task is mostly to deter smuggling and illegal immigration, and to perform SAR operations. A typical Coast Guard vessel that is used to patrol is the Panther 57 (Lambro57) (Figure 7), which is capable of achieving speeds over 40 kn. Its shallow draft and protective water jet intake grill make it capable of operating in waters as shallow as one meter deep. In contrast, it is equipped with only navigation radar and night vision binoculars, and due to small tonnage, it is extremely vulnerable to weather conditions. The general characteristics of this type of ship are depicted in Table 3.

Figure 7.   Hellenic Coast Guard's typical patrol boat (Panther 57) (From MotoMarine shipyards, www.motomarine.gr).

Table 3.   General characteristics of Panther 57

Length Overall	18.2 m
Beam (max.)	4.68 m
Draft	0.92 m
Displacement	28 tons
Max Speed	44 knots
Range	250 miles
Engines	2 Engine Type 12V Man
Weapons	0,50 Browning Automatic Cannon

3.   Hellenic Air Force

Surface Surveillance is not among the tasks of the Hellenic Air Force. Nevertheless, use of RF-4 aircraft can contribute to reconnaissance, especially during wartime or SAR operations in peacetime.

4.   Hellenic Army

The large number of islands in the Aegean Sea, either big habitable ones or small islets, forms a rare environment for operations. Being on an island one may have a view of the neighboring island(s) most of the time, and this allows a

person to obtain a clear understanding of the interim sea space. Trying to take advantage of this spatial uniqueness, the Hellenic Army has located a number of coastal (sea) and Ground Surveillance Radar BOR-A550 (Figure 8) suitable for army, border/coast guard and security applications. It combines surveillance of ground, sea and lower level airspace in a single radar system whereby moving targets will be detected, located, automatically classified and tracked day and night under severe weather conditions.

Furthermore, across the Greek coastline of the Eastern Aegean Sea islands, there are a large number of sites with observers equipped with basic vision tools (i.e., binoculars, night vision goggles). All the information about targets in the AOI is passed to the National Surveillance System so that all the stakeholders are aware of the RMP.

Figure 8.   Radar BOR-A 550 (From Hellenic Army, www.army.gr).

5.   NATO

The Maritime Command and Control Information System (MCCIS) is a military maritime command and control system that has been developed and maintained for members of NATO. The MCCIS assists strategic and tactical

commanders and their staffs in the decision making process. MCCIS is installed and in operational use at 61 sites in different countries, one of which is Greece. There are over 250 users. All the member states are encouraged to contribute to the RMP, and they also have the privilege of sharing all the data without censorship.

MCCIS electronically processes data from multiple sources, displays data in various command and control applications, and allows the user to manipulate this data. One important component in NATO's MDA is NATO's Maritime Safety and Security Information System (MSSIS), which is based around the acquisition and analysis of Automatic Identification System (AIS) data. This data is gathered from the AIS systems of NATO member states as well as by a number of other non-NATO states on the basis of bilateral agreements.

Once the MSSIS analysis is complete, the relevant data is fed into NATO's MCCIS, as shown in Figure 9. Data held within the MCCIS is classified as, in addition to containing the compiled picture created through MSSIS, it also includes intelligence data, classified surveillance data (from satellites and other sensors) and the real time location of NATO assets (such as warships). One of the reasons why the basic MSSIS is kept at an unclassified level, however, is to attract the participation of non-NATO states (European Commission, 2008).

As regards the acquisition and processing of surveillance data, maritime or otherwise, NATO does not have an explicit mandate as such. Instead such activities are to be implied from the content of Article 3 of the North Atlantic Treaty, which states: "In order more effectively to achieve the objectives of this Treaty, the Parties, separately and jointly, by means of continuous and effective self-help and mutual aid, will maintain and develop their individual and collective capacity to resist armed attack."
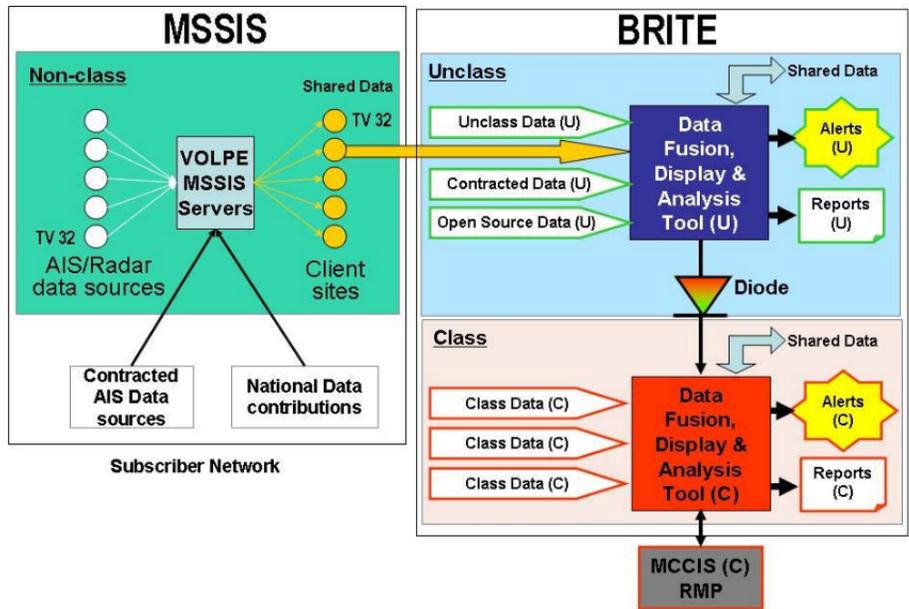
Figure 9. Diagram of MSSIS (From European Commission, 2008).

6. European Union

In 2004, the European Agency for the Management of Operational Cooperation at the External Borders of the Member States of the European Union (FRONTEX) was established, and its Eastern Sea Borders Centre is located in Piraeus, Greece. FRONTEX's mission is to help EU member states implement EU rules on external border controls and to coordinate operational cooperation between member states in the field of external border management.

While it remains the task of each member state to control its own borders, the agency is vested with the function of ensuring that they all do so with the same high standard of efficiency. To reduce duplicated effort and hence save time, money and other resources, the European Patrols Network was born in 2007. Greece, as guardian of the Eastern borders, has been assisted periodically by other EU countries with the deployment of a few patrol ships and aircraft.

The EU also has developed SafeSeaNet, a vessel traffic monitoring and information system, established to enhance maritime safety, port and maritime security, marine environment protection and efficiency of maritime traffic and

maritime transport. It was established as a centralized European platform to facilitate the maritime information sharing between European countries. The main sources of information consist of the AIS reports and notification messages sent by designated authorities in participating countries.

On February 13, 2008 the European Commission adopted a Communication on the creation of a European Border Surveillance System. It was designed to support the member states in their efforts to reduce the number of illegal immigrants entering the European Union by improving their situational awareness at their external borders and increasing the reaction capability of their information and border control authorities (Commission of the European Communities, 2008). It also focuses on the EU's southern and eastern maritime borders.

E. AIRBORNE PLATFORMS

Unmanned aircraft are commonly called unmanned aerial vehicles (UAVs), and when combined with ground control stations and data links, they form a UAS, or unmanned aerial system. Conventional wisdom states that the UAS offers two main advantages over manned aircraft: they are considered more cost-effective, and they minimize the risk to a pilot's life (U.S. Library of Congress, 2011). Because this study attempts to investigate the ways in which a UAS can be integrated into the current surveillance system, its basic applications and the major systems which might be used are being discussed in this section.

JP 3-52 defines a UAS as "that system whose components include the necessary equipment, network, and personnel to control an unmanned aircraft." According to this publication, the term UAS will be used instead of UAV across the U.S. Department of Defense. In this study the UAS Program of U.S. Navy is used as a reference, but the terms UAVs and UAS are used interchangeably.

1. Applications for UAVs

From the U.S. Navy's perspective, UAVs are currently being used in a large variety of applications. Of course not every UAV is capable of accomplishing all the missions, but each type of UAV is designed to carry different payloads and sensors; for this reason, UAVs can be used for a variety of applications. Some of the applications that the current UAVs are used for or for which they are about to be used in the near future are: penetrating strike, ISR operations, ELINT (intelligence derived from electromagnetic radiations from foreign sources) Collection, COMINT (technical and intelligence information derived from foreign communications) Collection, air-to-air combat, airborne electronic attack, suppression of enemy air defenses, close air support, chemical-biological-radiological-nuclear detection, battle damage assessments (BDA), mine detection, precision target designation, anti-submarine operations, suppression of enemy air defenses (SEAD) and psychological operations, such as dropping leaflets (Alkire, 2010; U.S. Library of Congress, 2011).

In a 2004 study, each Combatant Command and Service was asked to rank the importance of 18 missions relative to four general classes of UAS (i.e., small, tactical, theater, and combat). Their responses are depicted in Table 4. Although the distinction between the classes of UAS is not the same across time, it is notable that Reconnaissance, what we are most interested in for this study, is ranked as the highest priority regardless of the type of platform.

Table 4.   Combatant commander/service UAS mission prioritization matrix
(From Office of the Secretary of Defense, 2005).

Mission	Small	Tactical	Theater	Combat	JFC
Reconnaissance	1	1	1	1	BA
Signals Intel	10	3	2	5	BA
Mine Detection/CM	7	11	13	14	FP
Precision Target Location and Designation	2	2	3	2	FA
Battle Management	4	10	4	7	C2
Chem/Bio Reconnaissance	3	7	6	9	BA
Counter Cam/Con/Deception	8	5	7	11	BA
Electronic Warfare	14	9	10	4	FP
Combat SAR	6	8	8	10	FA
Communications/Data Relay	5	6	5	8	C2
Information Warfare	15	12	11	6	FA
Digital Mapping	11	13	9	12	BA
Littoral Undersea Warfare	17	15	14	13	FA
SOF Team Resupply	9	16	17	16	FL
Weaponization/Strike	16	4	12	3	FA
GPS Psuedolite	18	18	15	18	C2
Covert Sensor Insertion	12	14	16	15	BA
Decoy/Pathfinder	13	17	18	17	FA

Additionally, UAVs can provide critical support for SAR operations. However, to achieve their full potential, all the factors that affect the UAV's performance, such as payload capabilities, endurance, communications and environmental hazards, should be taken into consideration (Waharte & Trigoni, 1997).

Moreover, in this paper we are more interested in tasks that UASs can assume in the current framework of the HN. Therefore, in this section, traditional navy missions are emphasized rather than naval contributions to irregular warfare.

2. Types of UAVs

UAVs can be divided into many categories taking into consideration various factors like the missions they accomplish, their characteristics, the platform from which they are launched or their cost. According to the National Research Council (2005), the Navy views its future use of unmanned aerial vehicles to be primarily in three categories:

- Long-dwell, standoff intelligence, surveillance, and reconnaissance (ISR), as exemplified by the Broad Area Maritime Surveillance (BAMS) concept and the Global Hawk Maritime Demonstration (GHMD);

- Carrier-based, penetrating surveillance and SEAD/strike Joint Unmanned Combat Air System ; and

- Ship-based tactical surveillance and targeting, which call for a vertical takeoff- and-landing system that can operate from a variety of ship types.

As stated earlier, the U. S. Navy is making large investments in a number of major UAV programs, including BAMS, the Unmanned Combat Aircraft System Demonstrator, the Fire Scout vertical takeoff/landing tactical UAS (VTUAS), and the Small Tactical/Tier II UAS (STUAS/Tier II UAS) (Alkire, 2010). In general, UAVs can be launched from several platforms like shore bases or infrastructures, from surface ships or from aircraft carriers. Because the latter has no implementation in the HN, these vehicles are not studied in this paper. In the following section, we separate UASs into those categories that are of relevance to the HN and briefly present their main characteristics.

a. Broad Area Maritime Surveillance (BAMS)

The U.S. Navy is developing the BAMS unmanned system to provide a persistent, maritime, worldwide access, ISR capability (Figure 10). In FY 2003, the U.S. Navy purchased two RQ-4A Global Hawk variants with electro-optical/infrared (EO/IR) and SAR sensors, along with their ground control stations and support equipment. These are known as the GHMD System. It is a high-altitude, long-endurance (HALE) Unmanned Aerial Surveillance System and

provides the U.S. Navy with demonstration capability primarily for doctrine, concept of operations, and tactics, techniques, and procedures development. The BAMS UAS, named RQ-4N, is a maritime derivative of the Global Hawk equipped with Navy-specific control stations called Tactical Control Systems. It will have a full 360-degree field of regard and the capability to collect full motion video. It also requires a runway for takeoff and landing and is not carrier-capable (Alkire, 2010).
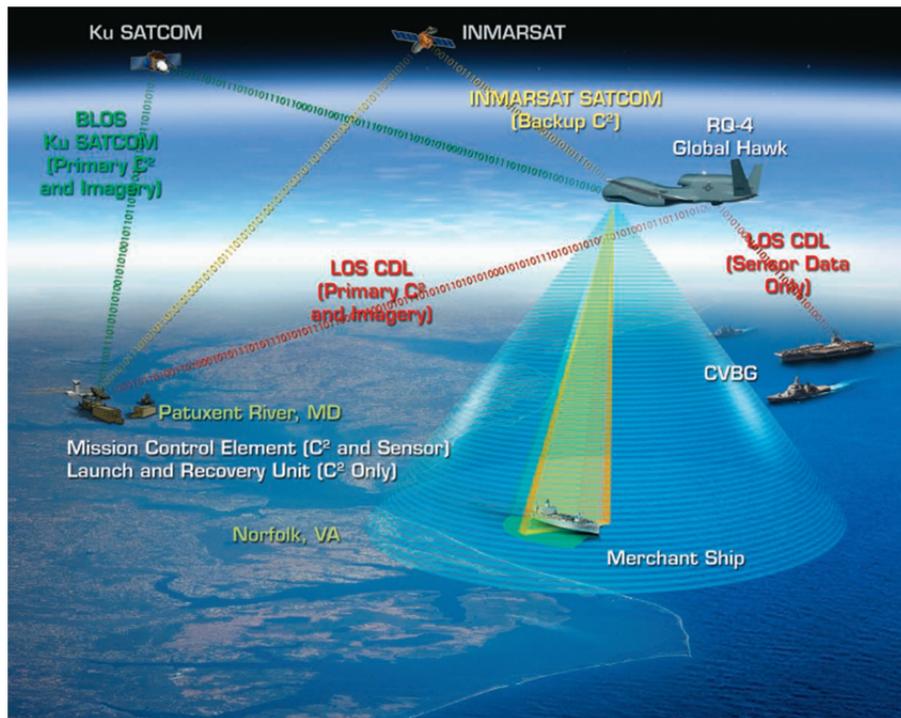
Figure 10. Graphical representation of BAMS Operations (From Northrop Grumman, www.northropgrumman.com).

The aircraft has a projected 12,000 nm range and 35-hour endurance, with satellite and line-of-sight communication links to the ground system. High resolution sensors that can look through adverse weather, day or night, from an altitude of 65,000 feet, can conduct limited maritime surveillance over an area the size of the state of Illinois in only 24 hours (Northrop Grumman, 2007). Detailed specifications are shown in Table 5.

Table 5.   Specifications of RQ-4 Global Hawk Maritime Demonstration System (From Northrop Grumman, www.northropgrumman.com).

RQ-4 Air Vehicle			
Wingspan	116.2 ft (35.4 m)	Height	14.6 ft (4.2 m)
Length	44.4 ft (13.5 m)	Gross Takeoff Weight	26,750 lbs (12,133.6 kg)
Payload	2,000 lbs (907.2 kg)	Maximum Altitude	65,000 ft (19.8 km)
Ferry Range	10,000 nm (18.520 km)	Loiter Velocity	343 knots
On-Station Endurance at 1,200 nm	24 Hours	Maximum Endurance	35 Hours
Sensors			
Synthetic Aperture Radar (SAR)	1.0/0.3 M Resolution (WAS/Spot)	Maritime Target Acquisition	Cue for ISAR
Maritime Search	15,000 sq. km/Min	ISAR	3 Resolutions
Electro-Optical	NIIRS 6.0/6.5 (WAS/Spot)	Infrared	NIIRS 5.0/5.5 (WAS/Spot)

b.   Vertical Takeoff/ Landing Tactical Unmanned Aerial Systems

The Fire Scout VTUAV system provides remarkable situation awareness and precision targeting support. The MQ-8B Fire Scout (Figure 11) has the ability to take off and land on any aviation-capable warship autonomously and at appropriate land areas without any special infrastructure.

Figure 11. MQ-8B Fire Scout (From America's Navy, www.navy.mil).

The Fire Scout VTUAS has an operational footprint that is a fraction of that of the multipurpose MH-60-class helicopters; it can operate from, and provide the UAS advantages to, surface ship platforms. The U.S. Navy has decided to replace helicopters with VTUAVs during the evolution of the Littoral Combat Ship program (Burgess, 2004). This type of UAV has been long tested and used by the U.S. Armed Forces. In 2009, 110 ship take-offs and landings were conducted, and during this time period the Fire Scout completed successful deployments in real combat fields (Jacobson, 2010).

The Fire Scout has an operating ceiling of 20,000 ft and a total endurance of over eight hours that provides more than six hours on station with a standard payload at 110 nm (200 km) from the launch site. A system of two Fire Scouts can provide continuous coverage at 110 nm. Utilizing a payload that includes EO/IR sensor with laser rangefinder/illuminator and maritime radar, the Fire Scout can find and identify tactical targets, track and illuminate them (Figure 12) and accurately provide targeting data to strike platforms (Northrop Grumman, 2012). Detailed characteristics are shown in Table 6.
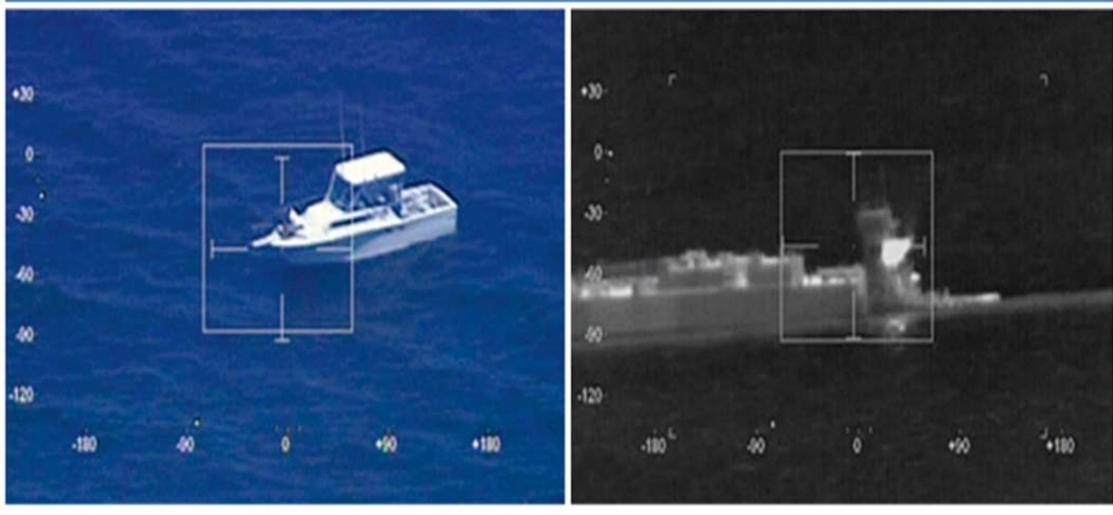
Figure 12. Images taken by MQ-8B Fire Scout's EO/IR sensors (From Northrop Grumman, www.NorthropGrumman.com).

Table 6. Specifications of MQ-8B Fire Scout (From Northrop Grumman, www.NorthropGrumman.com).

Fuselage Length (with Dual Payload Nose)	23.95 ft (7.3 m)
Fuselage Width	6.20 ft (1.9 m)
Length (with Blades Folded Forward)	30.03 ft (9.2 m)
Rotor Diameter	27.50 ft (8.4 m)
Height (Top of Tail Antenna)	9.71ft (2.9 m)
Gross Weight	3,150 lbs (1428.8 kg)
Engine	Rolls Royce 250-C20W Turboshaft Engine
Speed	115+ Knots
Ceiling	20,000 ft (6.1 km)
Total Flight Time with Baseline Payload	8+ Hrs
Total Flight Time with EO/IR + Radar	7+ Hrs
Total Flight Time with Maximum Payload	5+ Hrs
Payloads	EO/IR/LRF/Mine Detector/Comm.Relay/ Maritime Radar

The MQ-8B Fire Scout VTUAV is used to recapitalize the capability of the aging fleet of P-3 Orion aircraft and provide maritime domain awareness for the U.S. Navy (Alkire, 2010). The Fire Scout can be used in various missions, such as SSC, Birddog/tattletale operations, Maritime Interdiction Operations, BDA, ISR operations and Target Acquisition/Anti-Submarine Warfare, border patrol, SAR operations and medical resupply (Berner, 2004).

c.   Small Tactical/Tier II Unmanned Aerial Systems (STUAS)

In 2005, the U.S. Navy signed a $14.5 million contract with Boeing to provide ISR coverage with the Scan Eagle Small Tactical UAS (STUAS) (Alkire, 2010). In 2009, a Scan Eagle UAS was operated from a nearby U.S. Navy vessel to provide real-time situational awareness during a Somali pirate incident that ultimately ended with the safe release of the captain of a U.S. cargo ship. Following the successful tests and in-the-field support, in July 2010 the Department of the Navy awarded Insitu a two-year, $43.7 million contract for the design, development, integration and test of the STUAS Integrator RQ-21A for use by the Navy and Marine Corps (U.S. Library of Congress, 2012).

For the U.S. Navy, the RQ-21A (Figure 13) will provide persistent Reconnaissance, Surveillance, and Target Acquisition support for tactical maneuver decisions and unit-level force defense/force protection for Navy ships, Marine Corps land forces, Navy Expeditionary Combat Command forces and Navy Special Warfare Units (Small tactical unmanned aircraft system, n.d.). According to the manufacturer, upon completion of the project the RQ-21A will be able to handle the following missions: Search and Rescue, Disaster Response, Force Protection, Combined Arms, Target Following, Battle Damage Assessment, Pattern of Life, Border Security, Asset Protection, Wildlife Monitoring, Agricultural Assessment, Communications Relay, Networked Operations and Anti-Piracy (Insitu, 2012).

Figure 13. The Integrator RQ-21A is recovered with Insitu's SkyHook capture rope after its first operational take offs and landings at sea from the *San Antonio* class dock landing ship *USS Mesa Verde* (LPD-19) in the Gulf of Mexico on 10 February 2013 (From Naval Drones, www.navaldrones.com).

The RQ-21A will consist of a number of Air Vehicles (AVs), Ground Control Systems (GCS) and multi-mission payloads, which will provide intelligence coverage, surveillance, reconnaissance, and communications relay for up to 15 hours per day continuously with a short surge capability for 24 hours a day. Payloads include Day/Night Full Motion Video cameras, infrared marker, laser range finder and AIS receivers. Ancillary equipment includes launch/recovery mechanisms, tactical communications equipment and spares. The RQ-21A will have a minimal operating radius of 50 nm, and the AV will be capable of airspeeds up to 80 nm per hour (knots) with a service ceiling of 15,000 ft density altitude. The fully autonomous launch and recovery system will require minimal space for takeoff and recovery from an unimproved expeditionary/urban environment, as well as from the deck of Navy ships. Initial operational capability is planned for 2013 (Small tactical unmanned aircraft

system, n.d.). Characteristics of UAS Integrator (RQ-21A) are depicted in Table 7.

Table 7. Specifications of Integrator (RQ-21A) (Insitu, 2012).

Wingspan:	16 ft / 4.8 m
Length:	7.2 ft / 2.2 m
Empty structure weight:	80 lb / 34.0 kg
Max takeoff weight:	135 lb / 61.2 kg
Max horizontal speed:	80+ knots / 41.2+ m/s
Cruise speed:	55 knots / 28.3 m/s
Ceiling	>15,000 ft / 4,573 m
Endurance:	24 hours
Payloads	Electro-optic, Mid-wave infrared, IR marker*, Laser rangefinder* * Class 3B laser product.

F. DETECTION PROBLEM AND RELATED STUDIES

This section briefly discusses the problem of detection, which involves the major issues that impede the detection and identification procedure, as well as the most important studies made on surveillance from UAVs either on the ground or in the maritime domain.

1. Detection Problem

The detection and identification problem, as one can easily understand, is very complex as it involves a variety of sensors and agencies. The sensors involved are mostly Radio Detection and Ranging (RADAR or radar) systems and Electro-optical/Infrared (EO/IO) sensors. Radar systems are active sensors that emit electromagnetic waves which are reflected from targets and then received back by their sensors. Compared to EO/IR systems, radar systems have almost the same performance during day or night under clear weather, but radar systems suffer less atmospheric attenuation than EO/IR systems. For this reason, they are able to detect targets at greater ranges.

Conversely, EO/IR systems are passive devices and work with the radiations emitted by the target. EO sensors provide visual images of the targets

and are mostly used during day. However, they are limited by any factor (such as clouds, smog or camouflage) that hampers visual contact between the sensor and the target. IR cameras transform the thermal energy that the targets emit to a video signal. The drawback of IR sensors is that they cannot provide accurate image details of the target, but an experienced user can easily determine the type of target from the resulting image. In the field, units with EO/IR sensors are used to identify targets that have already been detected by other sensors (radar, other reports, intelligence, etc.) because in that way the target information is received in less time (Brown & Schulz, 2009).

Taking into consideration that UAVs are based on the EO/IR that they carry, sea state and adverse weather conditions, such as rain droplets, snow, fog and hail stones, will all affect their operation. Moreover, limited endurance or incapability to operate in the aforementioned weather conditions may influence the UAV's performance. These conditions may affect the unmanned vehicle itself or the platform from which it is launched (Johnson, 2004).

Perhaps the most important factor that affects the IR performance is rain. Precipitation causes attenuation of the signal (Figure 14) and also could result in a loss of communication between the GCS and the UAV because radio frequencies are often used for the communication channel. The impact of surface clutter diminishes EO/IR sensor effectiveness, as well (Johnson, 2004).
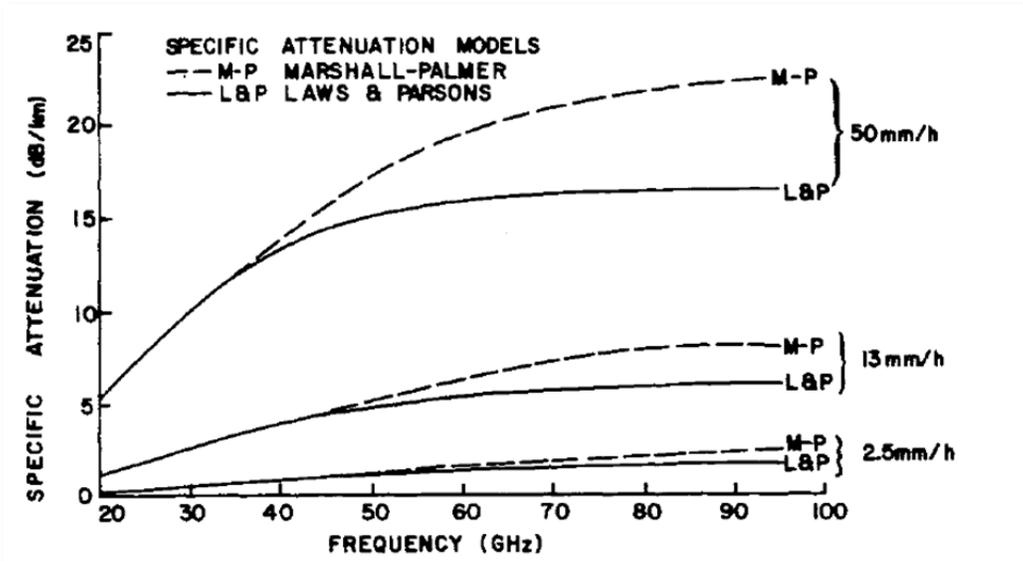
Figure 14. Specific attenuation for rain calculated for two model drop size distributions (From Crane, 1981).

The target resolution of a radar system has the ability to distinguish between targets that are very close in either range or bearing. Weapons-control radar, which requires great precision, should be able to distinguish between targets that are only yards apart. Search radar is usually less precise and only distinguishes between targets that are hundreds of yards or even miles apart. Resolution is usually divided into two categories: range resolution and bearing resolution.

Range resolution is the ability of a radar system to distinguish between two or more targets on the same bearing but at different ranges (Figure 15). The degree of range resolution depends on the width of the transmitted pulse, the types and sizes of targets and the efficiency of the receiver and indicator. Pulse width is the primary factor in range resolution.
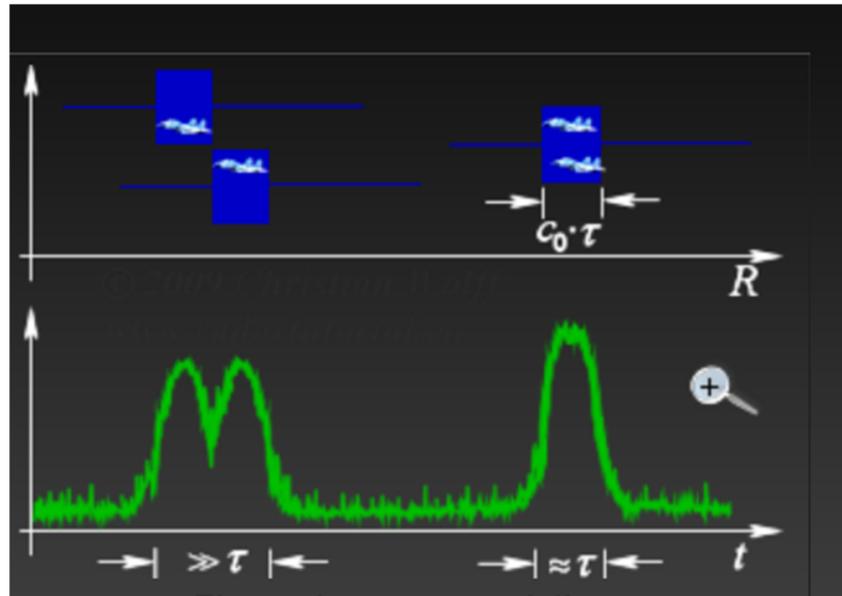
Figure 15. Range Resolution. The left pair of targets in closer distance is detected, but the right one at a greater distance is not (From Radar Tutorial, www.radartutorial.eu).

2.   Related Studies

In this section, we provide an overview of studies that investigated how the type of UAVs used can affect their tactics. For example, the payload a UAV can carry determines the way it will be used. If a UAV has long endurance, it will be assigned to cover large areas; if this is not the case, then operational priorities will have to be set. Furthermore, the platforms from which they are launched along with the extent to which they are affected by adverse weather conditions are crucial for operational or tactical commanders to take into consideration. In addition, the number of UAVs needed to complete the identification mission is dependent upon the size of the search area and the sweep-width of a UAV's sensors (Washburn, 2002).

Berner (2004) studied the effective use of multiple UAVs for the Navy's SSC Mission. More precisely, he studied how a BAMS UAV and VTUAVs working together can provide increased situational awareness in the maritime environment. The best UAV combination is BAMS plus two or three VTUAVs.

However, Berner's analysis showed that small numbers of VTUAVs can perform as well without BAMS as they do with BAMS. For combinations with multiple UAVs, BAMS proves to be a valuable asset that not only reduces the number of missed classifications, but greatly improves the amount of coverage on all contacts in the maritime environment. BAMS tactics have less effect than the mere presence of BAMS itself.

Lalis (2007), using agent-based simulation (MANA), identified that the most important factors when planning UAV operations are the size of the area being covered, the Time on Task (ToT) and the detection range of the UAV. He also assumed that the UAV's probability of detection is perfect (Probability of Detection=1) when a target is within a radius of 2–18 nm ("cookie-cutter" approach). This led to the conclusion that the length of the shoreline has no impact on the target's survivability because UAVs fly over the whole coastline. Lalis also studied the effect of the UAV's three search patterns on target detection and concluded that "if ToT is not under consideration, then the three patterns are not different." Conversely, other study suggests that "the patterns that UAVs fly have a direct effect on the coverage area and probability of detection of contacts of interest" (Gottfried, 2004).

McMindes (2005) studied the impact of a wide variety of factors, such as UAV speed, stealth, altitude and sensor range, as well as enemy force sensor ranges, probability of kill, array of forces and numerical strength on the UAV's survivability. He concluded that a speed between 135 and 225 kn increases the UAV's survivability. The exception to speed's dominance is in the face of extremely high capability enemy assets. In this case, stealth becomes more important than speed alone. However, the interactions indicate that as both speed and stealth increase, speed yields a faster return on overall survivability, and that speed mitigates increased enemy capabilities. Concerning altitude, increased altitude produces higher mean survivability as well as decreased variability.

Yildiz (2009) studied the use of mini-UAVs in border security and found them to be beneficial in capturing the illegal entrants and thus could potentially provide more secure borders. Adequate manpower and a reliable communication scheme to compose a COP emerged as the most important factors.

G.   TASK ANALYSIS

EO/IR systems produce images that must be scanned for recognizable patterns of targets. Computers have an ability to scan imagery continuously for long periods of time without risk of degraded performance due to boredom or fatigue. Humans, on the other hand, are characterized by a greater capability to pattern match visual images, but they are susceptible to performance errors. Combining computer and human analysis allows for the benefits of each resource to be utilized resulting in enhanced capabilities. The analysis of EO/IR images can be done at the location of the sensor or at a central location (Brown & Schulz, 2009).

In this section we conduct a task analysis, because it is the process that describes the user's task in detail and helps stakeholders to design a system that supports users in doing this task in the most effective way. Task analysis has long been used as a fundamental step in system design and is useful for examining new or existing systems. Understanding the process and task structure of target detection may shed more light on how surveillance can be conducted.

Because the surveillance task used in this study is very complex and incorporates inputs from and activities performed by many field users, we subdivide it into four distinct subtasks. These subtasks are: communications, search, detection and identification. The subdivision of a system into autonomous tasks is, in general, a powerful technique for studying a complex system. In the case of distributed surveillance systems, the subdivision of a system into elementary modules is necessary for the distribution of intelligence (Marcerano et. al, 2001).

Note that the following task analysis (Table 8) refers to a high level of command because too many details would be out of the scope of this study.

Table 8.   Maritime surveillance task analysis.

No	Task	Subtask/ user action	System Actions
1	Establish communications	1.1 Operate the appropriate communication devices	Telephones, VHF, UHF, Link 11-14
		1.2 Get familiar with the functionalities and the military procedures	
		1.3 Take measures against information leakage	Implement corresponding doctrines
		1.4 Set up communication with other partners	Set up communication with your collaborators

2	Search	2.1 Gather information concerning weather conditions	Sea state, visibility, wind direction & strength, rain
		2.2 Allocate the units to cover all the area of responsibility	If this is not feasible, give priorities
		2.3 Take into consideration information for potential targets in the area	Use the information to conduct search more intensely
		2.4 Define the search pattern for the subordinate units	Search an area/search around a specific position
		2.5 Approach the shoreline to detect potential targets which electronic devices cannot detect due to technical restrictions	Being closer to the shoreline the radar resolution is increased
		2.6 Eliminate blind sectors	
		2.7 Search for electronic emissions (if available)	IFF, monitor AIS system, ESM
		2.8 Minimize the depth of overlapping sectors	Searching in adjacent sectors should not be extensively overlapped in order to reduce the cost
		2.9 Report unit position according to the procedures	

3	Detection	3.1 Record time and position of the detected target	
		3.2 Match the detection with information for potential target in the area	Are you expecting a target in this area or not?
		3.3 Search more thoroughly in the area close to it for additional targets	Approach the target to have better visual contact and increase radar resolution
		3.4 Verify that it is not a pseudo-target	Tune your device for optimum performance
		3.5 Report its time and speed	
4	Identification	4.1 Correlate information provided by other agencies to identify the detected target	What type of target am I expecting in this area?
		4.2 Identify visually the detected target	
		4.3 Identify the target using electronic devices	Identify positively the target using devices (electro optical , I/R)
		4.4 Identify the target by its electronic emissions (if available)	IFF, monitor AIS system, ESM
		4.5 Report its identity	
		4.6 Keep continuous contact with the identified target	
		4.7 Record its electronic emissions in the data base (if available)	Enrich the corresponding data base for future use

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III.   MODEL DEVELOPMENT

A.   MODEL SELECTION

Models are used to represent and describe the behavior of the system being modeled. Models assist users in gaining a better understanding of the real world, and in most cases they present real systems in a simplified way. In general, models are the most cost-effective way to study a system. They are also a risk-free solution in cases where dealing with the actual system itself might put the user in danger. Another benefit of models is their ability to reduce the time, space, and means needed to study a system (Sanchez, 2007).

"A system is defined to be a collection of entities that act and interact together toward the accomplishment of some logical end. In practice, what is meant by system depends on the objectives of a particular study" (Law, 2007). Systems can be classified in a variety of ways. In this study we focus on simulation solutions to study the efficacy of using UAVs to monitor a complex marine environment.
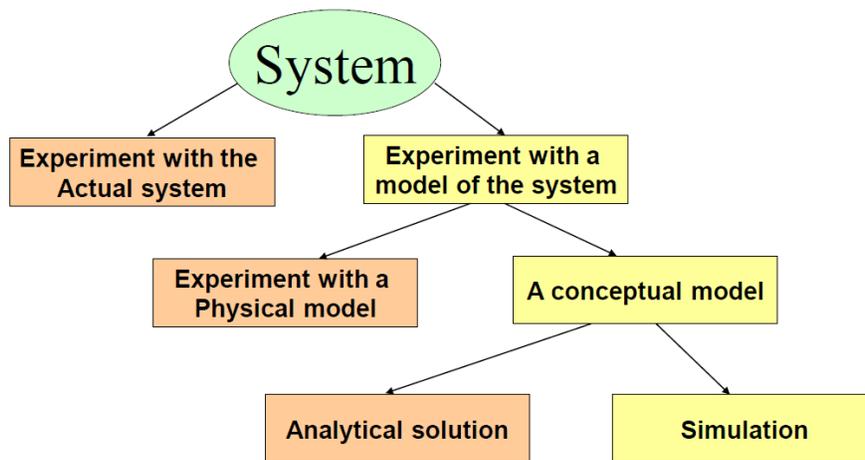
Figure 16.   Ways to study a system (From Law, 2007).

Analytical solutions are preferred when the elements that compose the model are relatively simple. Using such an approach, it is possible to obtain a closed-form solution and get a precise answer. These methods may involve algebra, calculus, probability theory, linear programming, decision analysis, Markov chain analysis and queuing theory (Law, 2007, pp. 3–6; Berner, 2004). However, when a system is highly complex and an analytical solution is infeasible, we use simulation solutions, instead. In a simulation, we use a computer to evaluate a model numerically, and data are gathered to estimate the desired true characteristics of the model (Law, 2007).

Simulation has both advantages and disadvantages, and every user/analyst should be aware of them. By simulating a system, we numerically exercise the model to investigate how the inputs affect the output measures of performance. That means that we are capable of making predictions of input changes. Additionally, visualization can give a good understating of a system and allow us to study its behavior in detail. On the other hand, a simulation, as are all models, is limited by its assumptions. Some assumptions may be reasonable, but some may be implemented solely to make the model less complex. In any case, these assumptions are set by the user, and in altering these assumptions, we change the output, yielding a less robust solution. Furthermore, in some cases, it can be time consuming to try to build complex models with debatable results.

B. MAP-AWARE NONUNIFORM AUTOMATA

In this study, the Map-Aware Non-uniform Automata (MANA) Version V software is used as the simulation tool. This section explains the reasons that this model was chosen and describes briefly its major features.

1. Overview of MANA

MANA is an agent-based, time-stepped simulation modeling environment. Agent-based models seem to be the most appropriate for the current study because of their ability to describe the behavior of individual entities in complex systems. MANA is a Discrete Time Simulation (DTS), which uses a fixed time

increment as the time advance method (Alrowaei, 2011). DTS is the most commonly used time advance mechanism in combat simulation and agent-based models (Macal, 2010, pp. 371-382). The fact that MANA also has been used in numerous Naval Postgraduate School theses and in other studies in the military domain indicates its usefulness.

MANA has been built upon two key ideas. The first idea describes how the model will contain entities that are controlled by decision-making algorithms. These entities (agents) interact with each other, as well as the environment in which they operate, and make their own decisions based upon the "personality" the modeler gave to them. The second idea has to do with the simplicity of the model. The creators of MANA claim that more detailed models are not necessarily better (McIntosh, 2007). Additionally, the non-linear nature of equations describing real situations is sensitive to initial conditions resulting in non-robust solutions (McIntosh, 2007). Perhaps, this is the biggest benefit of MANA; although it is designed to describe complex systems, like any other simulation tool, it does so with comparatively simple models.

MANA is intended to address a wide spectrum of problems and was designed for use in scenario exploring. That is, the modeler can vary the parameters of the model, even while it is running, and observe the output. This feature is a great benefit for the analysts because they have the capability to explore the relative importance of a variable on the final result. Furthermore, MANA is user-friendly and allows the modeler to create his/her own scenario in a short time using a very simple and understandable interface. Building the appropriate scenario, the user can explore how the agents perform and gain insights about the potential outcomes.

2.   MANA Characteristics

In this section, the innovative features of MANA compared to other models, along with its basic characteristics, is briefly discussed. The most important elements of MANA and its concepts are presented to provide the

reader with information most relevant to this study. For further details see McIntosh (2007).

- *Agent* is the individual entity that "operates" in the scenario. Each entity has certain personality traits that drive it toward or away from other entities, waypoints or areas with specific characteristics (i.e., areas that provide cover or areas in which it is easier to move). An agent is also equipped with sensors, weapons and speed of movement, all of them with capabilities arranged by the modeler. It may also have established communication links with other entities.

- *Squad* is a group of agents of any size, as defined by the user. Agents in a squad share the same propensities, the same capabilities and the same SA Map. In a naval scenario, like those studied in this thesis, a squad may be considered as a squadron of ships of the same type.

- *Battlefield* is the area in which the scenario is taking place. Unlike previous versions, in MANA V battlefield distances and agent speeds can be specified directly in terms of real-world distances and times. The battlefield time interval can be set by the user. The shorter the time interval, the more accurate models we have, but more calculations are needed resulting in more time consuming simulation runs. A background map can be loaded for illustrative purposes without any impact on the simulation run. In contrast, terrain maps can be used to identify terrain features. These maps (Figure 17) are standard Windows bitmap files, which use colors to impact the agent movement in the battlefield. Apart from the default colors, the user can create various colors to capture terrains with different characteristics with respect to three factors: Going, Cover and Concealment (Table 9). These factors act as multipliers to movement speed, hit rate and sensor detection, respectively. For example, if an area has been defined to have Going=0, Cover=1 and Concealment=1 then the agent who will be there will not be able to move, he cannot be shot at, and no one can see him.
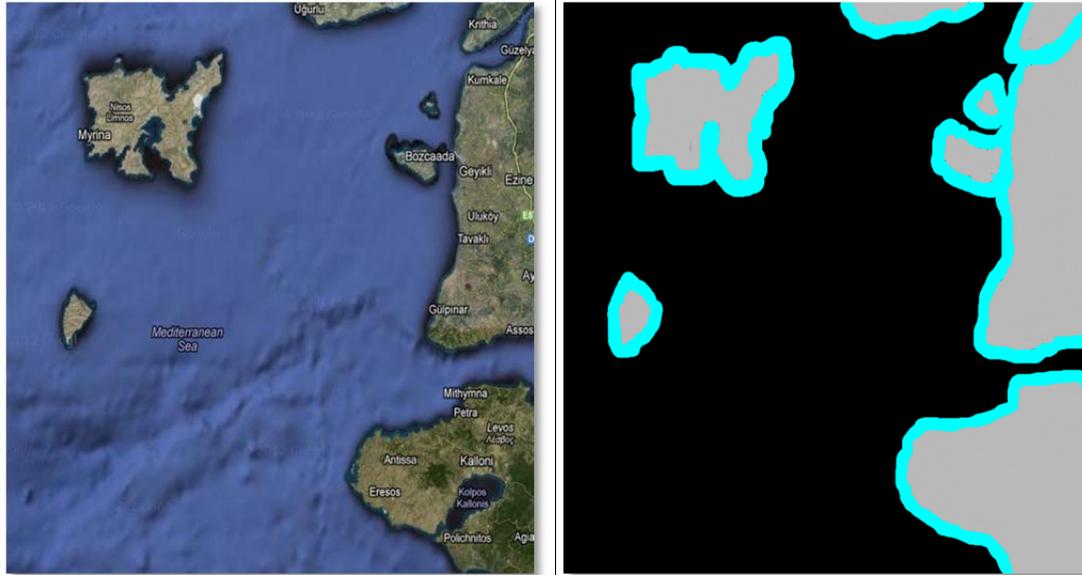
Figure 17. Background Map (left) used in a scenario in MANA. Terrain Map (right) for the same scenario. The values that have been set for the colors in the Terrain Map are noted in Table 9.

Table 9.   Values for Going/Cover/Concealment of the Terrain Map depicted in Figure 17.

Name	Going	Cover	Concealment	Color
Sea	1.00	0.00	0.00	Black
Land	0.10	0.00	0.00	Grey
Near Land	0.75	0.50	0.50	Light Green

- *Trigger State* feature provides MANA with additional flexibility. As the scenario evolves, certain events may occur to an agent (or its squad). These events might be the presence of an enemy in its vicinity, the arrival at a waypoint, a shot taken, an agent injury and many more. If an event happens, the modeler can define a new set of agent personality weightings, speed, sensor capabilities or any other parameter that "describes" this agent. The modeler is able also to define the time that the agent shifts in the new "trigger state," as well as a potential sequence of trigger states, enhancing the agent's behavior which might emerge in a scenario.

- *Sensors* are critical features for the agents. Each entity can carry up to six sensors, either simple or advanced. "Simple sensors only

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provide a cookie-cutter model of detection and classification while advanced sensors allow the specification of a range-integration time profile for both" (McIntosh, 2007). The term "cookie-cutter" means every visible contact within the detection range will be detected (or classified for the case of a classification range). On the other hand, the advanced sensor type uses times between detections with respect to the range solely for the detection task. For the classification, it uses range-dependent probability of classifying detecting events. It is important to note that detection is a prerequisite for classification.

- *Situational Awareness (SA) Map* is one of the innovative elements of MANA. It is graphical representation of a squad's perception of the battlefield. That is, it is a map that depicts the contacts (classified or not) of which the squad is aware. It represents intra-squad communications whereby squad members actively share information, as it would be expected in a real combat team. The modeler can also define the time taken for information to get from the agents' sensors to SA Map. This definition models potential time delays in information sharing.

- *Inorganic SA Map* represents information obtained remotely from other squads, as opposed to the squad's own sensors. The modeler defines which squads could communicate as well as the quality of the communication with respect to several different parameters such as Latency, Reliability, Capacity and Filtering of information. Figure 18 is a snapshot of an SA Map and an Inorganic SA Map for the same time of a simulation run. The main difference between the two is that, in the second, only contacts coming in from remote squads will be displayed. In reality, the agent is aware of both the pictures. With all these features, MANA is an appropriate tool to study aspects of network centric warfare.
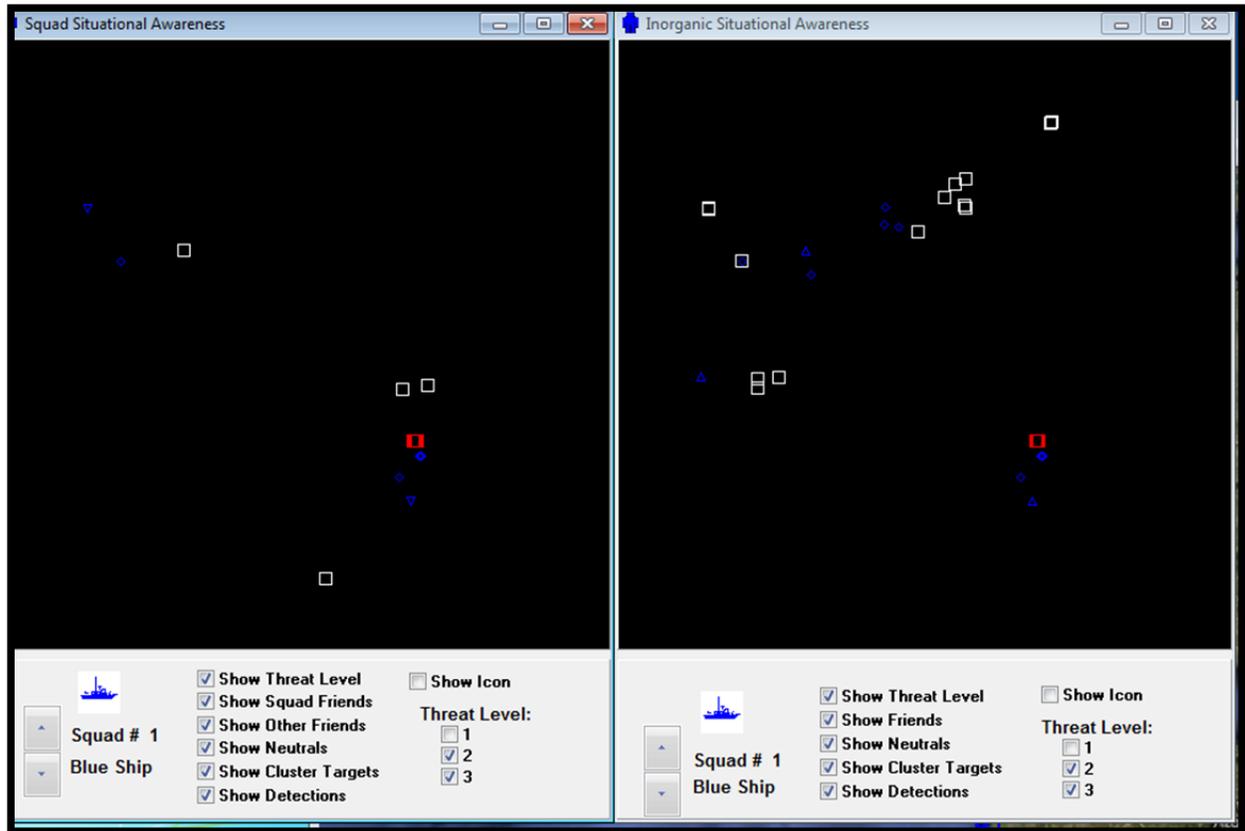
Figure 18. Snapshot of SA Map (left) and Inorganic SA Map (right), concerning Squad 1, for the same time of the simulation run. Fellow squad members are represented by triangles, other friendly targets are represented by inverted triangles, enemies are represented by (red) squares and neutral targets are represented by (blue) inverted squares. Unknown contacts are represented by white rectangles.

- *Fuel* is one more innovative property of MANA. It does not necessarily refer to fuel, food or other supplies, but it can be used to record interactions with other agents or to assist in shifting into certain trigger states. The modeler can define several parameters such as refuel range, probability to refuel enemy/ friend/ neutral and refuel rate. This feature is used extensively in our model and will be explained in detail later.

C. MODEL IMPLEMENTATION

1. Models in MANA

As described in previous chapters, the Aegean Sea is an extremely complex environment because it consists of areas either of "open sea," where a ship can sail for about 50 nautical miles without the "coverage" of nearby islands, or areas where "many islands" are very close to one another. These rare geographical conditions compose a challenging environment operationally. The effectiveness of UAVs is studied separately in those two environments creating two different models, as described in the following sections.

a. "Open Sea" Model

The "Open Sea" model represents a typical area of the Northern and Southern Aegean Sea. In this model (Figure 19), the Red Force consists of four surface vessels. These vessels attempt to transport illegal immigrants to the small island on the Southwest. To succeed in their mission they have to sail the open sea without being detected by the Blue Surveillance System. To increase the possibility of going undetected, they keep close to nearby merchant vessels that have approximately the same course with them. They have no communication capabilities, but it is assumed that they have the same tactic.
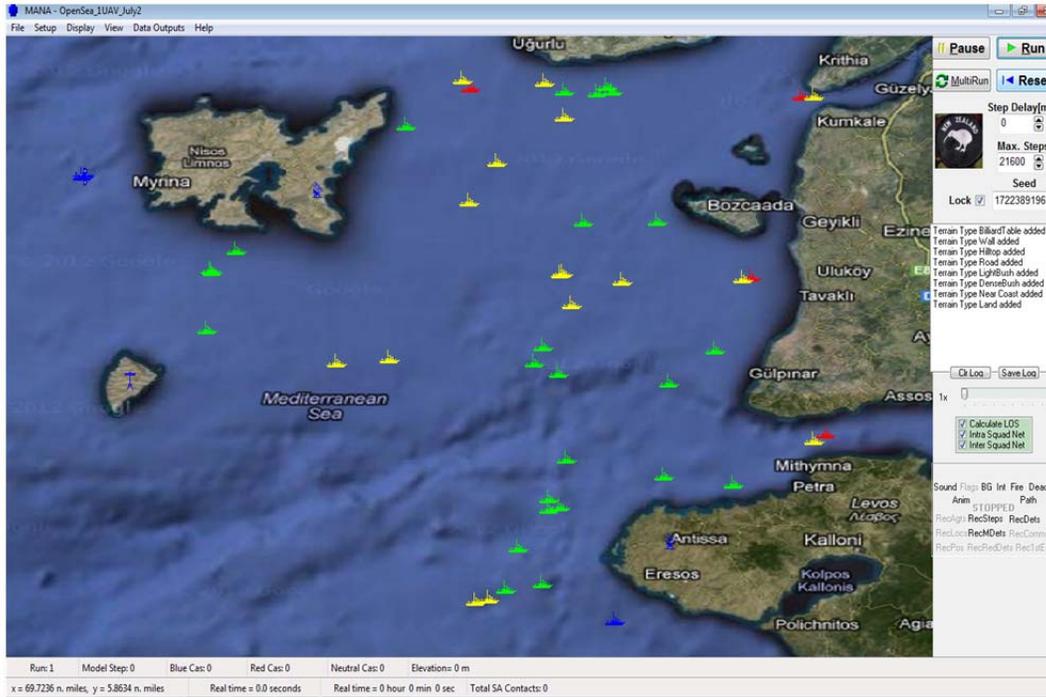
Figure 19. "Open Sea" model implemented in MANA.

The Blue Force, which has the responsibility to monitor the AOI, consists of two ground radars, located on the Northwest and Southeast islands respectively, as well as two Blue surface ships which patrol in two different sectors. In variations of this model, we study the effect of one or two UAVs on the performance of the surveillance system.

In the area, there are a large number of merchant vessels (yellow ships) that sail along specific transit lanes either northbound, or southbound. In the Northeast corner are the Dardanelles Straights, which link the East Mediterranean with the Black Sea, and are usually characterized by high traffic. Additionally, there are randomly scattered fishing vessels (green ships), something very common in the area.

b.   "Many Islands" Model

The "Many Islands" model represents a typical area of the Central and Southeast Aegean Sea. In this model (Figure 20), the Red Force consists of

four surface vessels which, again, attempt to transport illegal immigrants beyond the islands on the West. To succeed in their mission they have to sail westbound without being detected by the Blue Surveillance System. To increase the possibility of going undetected, they do not sail directly to the final destination; instead they sail close to the shoreline during their route. They have no communication between them, but it is assumed that they have the same tactic.
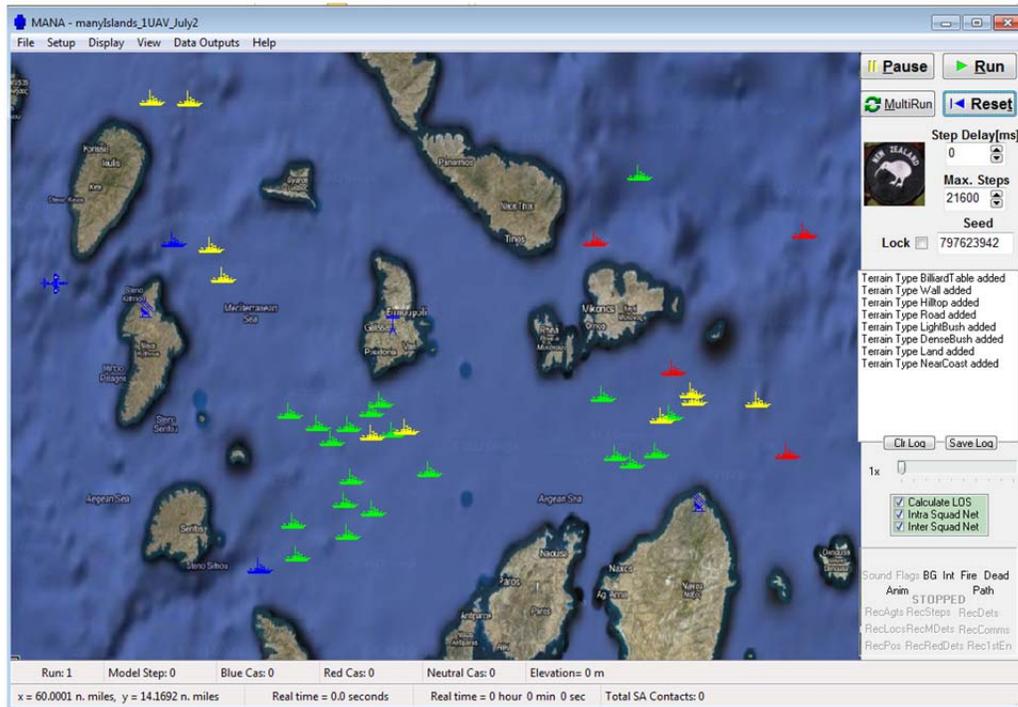
Figure 20.   "Many Islands" model implemented in MANA.

The Blue Force, which is responsible for monitoring the AOI, consists of two ground radars located on the West and Southeast islands, respectively, as well as two Blue surface ships that patrol in two different sectors. In variations of this model, we study the effect of one or two UAVs on the performance of the surveillance system.

In the area, there are a large number of merchant vessels (yellow ships) that sail in various routes. This represents the movement of merchant

vessels, cruise ships or coastal shipping. Additionally, there are randomly scattered fishing vessels (green ships), something very common in the area.

2. Assumptions

Every model is subject to assumptions which limit it in specific circumstances. The models that are demonstrated in this study have the following assumptions:

- No intelligence from other resources is taken into account. The Blue and Red forces are based only on the information taken from their own sensors.

- The Red ships cannot communicate with each other to exchange information about the adversaries.

- The size of the Red surface vessels is expected to be medium, such as fast patrol boats or fast motor boats. This factor affects the detection range, as explained in Chapter II.

- The Red ships do not start sailing towards their goal unless they meet a merchant vessel that is sailing to the same area ("Open Sea" model).

- The Blue UAVs and Blue ships get close to the enemy and remain there for a period of time only once. Operationally, it is reasonable for Blue sensors to gather information about a specific target one time. When a target has been lost, but we expect it to be in a specific area, we are satisfied if only one of our sensors locates it.

- Blue ships and UAVs spend time close to enemy targets only to collect information (photos, electronic emissions, etc.). This is not necessary for merchant and fishing vessels because once it is known that the contact is neutral, the Blue units immediately move to the next unidentified contact or, if there is none, along their patrol route.

3. Measures of Effectiveness (MOE)

It is desirable for the Blue Force to monitor the AOI consistently. That means that we want them to detect and identify as many targets as they can but also to keep contact with the targets as much time as possible. Detecting and then losing a target gives only a piece of information on the target's existence and nothing about its current location. For this reason, it is considered that a

more robust MOE to evaluate the system's performance is the "Proportion of time Red Ships are positively identified" and "Proportion of time Merchant Vessels are positively identified." We expect the two MOEs to be highly correlated, but we also want to investigate whether the surveillance system performs differently with respect to the type of contact.

4. Agents Description

As mentioned earlier, a squad is a group of agents that have the same characteristics. Every agent has a unique allegiance that depicts the agent's side during the model run. It can be on the Blue side (Allegiance 1), on the Red side (Allegiance 2) or neutral (Allegiance 0). MANA offers additional features, such "Threat Level" and "Class," so that differentiations among the agents can be expressed. All the agents used in the "Open Sea" model, along with their allegiance, threat level and class, are shown in Table 10. The same agents with similar characteristics are also used in the "Many Islands" model.

Table 10.   Agents used in the "Open Sea" and "Many Islands" models

Agent's Name	Agent's Allegiance	Agent's Threat Level	Agent's Class
Blue UAV	1	3	7
Blue Ship	1	3	1
Blue Ground Radar 1	1	3	3
Blue Ground Radar 2	1	3	4
Blue Operational Centre	1	2	0
Red Ship	2	3	0
Merchant Vessel	0	3	0
Fishing Vessel	0	1	0

a.   Blue Ships

In every model there are two surface Blue ships. At the beginning of each scenario, the Blue ships patrol along a specific route covering different sectors. Together, along with the other Blue sensors described in this section, they cover all the AOI. The patrol route is focused near the coastline, as well as inside the territorial waters, to detect potential hidden targets. They exchange information with the Operational Centre to have improved SA. Initially, a Blue ship has a higher propensity to move towards unknown contacts in order to identify them (Figure 21). If it meets an enemy (Red ship), it sails towards it ("Enemy Contact 3" state) and stays close to it for more than 15 minutes (1000 time steps).
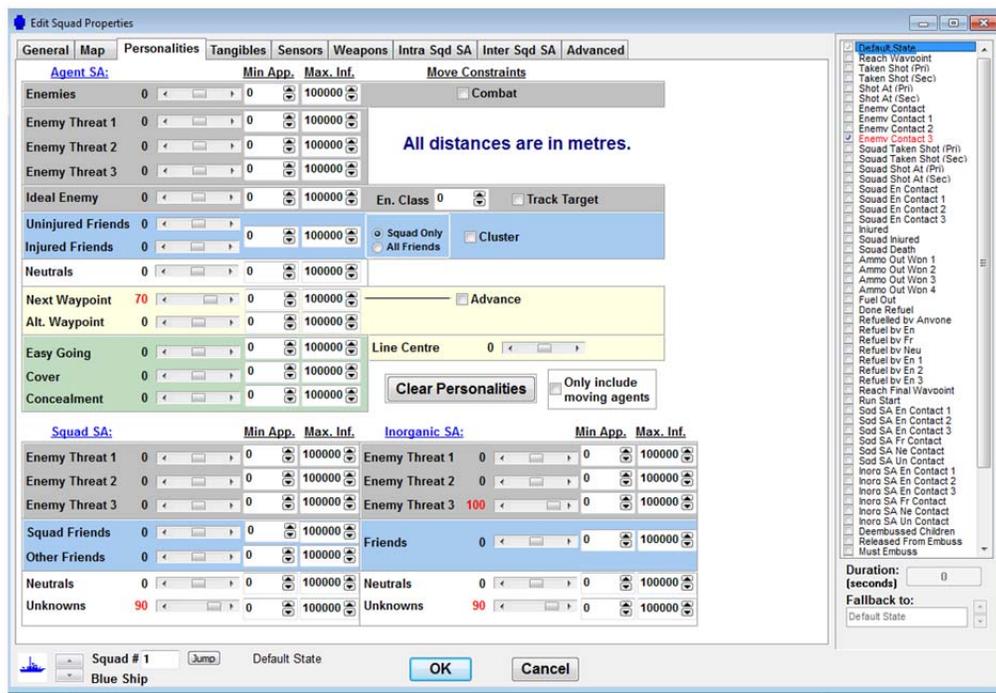
Figure 21. Personalities tab of the Blue ship agent for the default state.

This time is provided to collect all the information needed (photos, electronic emissions, etc.). Nothing is capable of interrupting this mission. After this time has passed, the Blue ship shifts to the "Spare 1" state where it shoots at

the enemy (with zero probability of success). This is only to help the Red ship to shift to the "Shot At" state, so that the Blue unit breaks lock of it. Once the Blue ship stops monitoring the enemy target, it sails towards other unidentified contacts or, if there is none, along its patrol route. To avoid engaging on the same target with other friendly forces, the Squad Friendly Awareness has been set to -100. Finally, the Blue ship is equipped with a detecting sensor. In this study the Advanced Sensor Model is used. The detection range has been divided into five zones, and each one has different detection probability. It is more accurate to consider that a target closer to the detecting sensor has a higher probability of being detected than a target close to the maximum range. The same method is applied for the Classification Probabilities (Figure 22). Finally, when a Blue ship identifies a target, it "refuels" it with a rate of 1 fuel unit per time step. At the end of each simulation run, the remaining "fuel" is used to calculate the time a target was monitored.
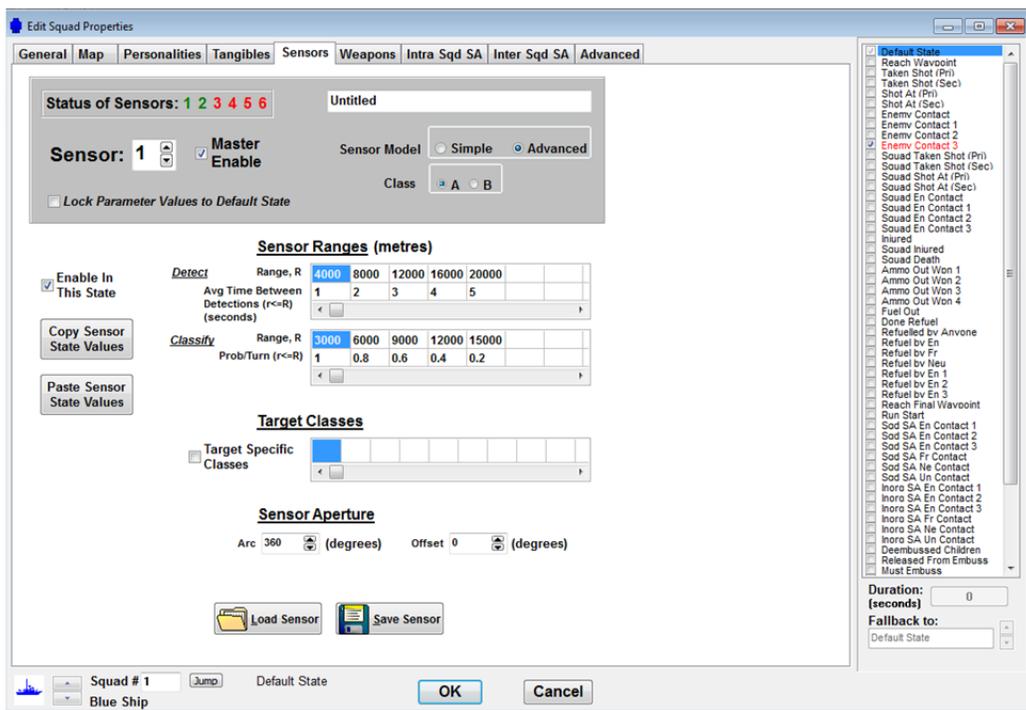
Figure 22. Sensors tab of the Blue ship agent.

b. Blue UAV

Every model is studied having one or two UAVs available. The Blue UAVs have similar behavior to the Blue ships. If one UAV is available, it starts its patrol from the Northwest area (Figure 23), where the first Blue ship is located. The patrol route is focused near the coastline, as well as inside territorial and international waters, to detect potential hidden targets. If a second UAV is available, it starts from the Southeast area in the "Open Sea" model, where the second Blue ship is located (in the case of the "Many Islands" model, it starts from the Southwest area). In that case, the two UAVs cover different sectors. Together, along with the other Blue sensors described in this section, they cover all the AOI. They pass information to the Operational Centre and receive information from the nearest ground radar.
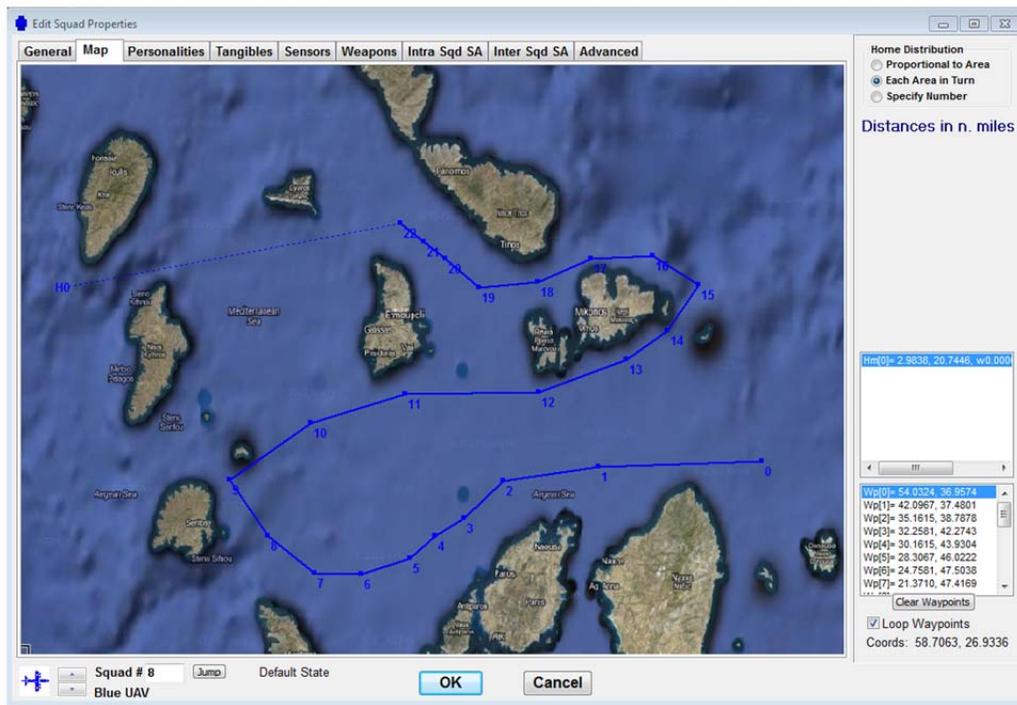
Figure 23. Map Tab of the Blue UAV agent in the "Many Island" model with one UAV available.

Initially, the Blue UAV has a higher propensity to move towards unknown contacts in order to identify them. If it meets an enemy (Red ship), it sails towards it ("Enemy Contact 3" state) and stays close to it for more than 15 minutes (1000 time steps). This time is provided to collect all the information needed (photos, electronic emissions, etc.). Nothing is capable of interrupting this mission. After this time is passed, the Blue UAV shifts to the "Spare 1" state, where it shoots at the enemy (with zero probability of success). This is only to help the Red ship to shift to the "Shot At" state, so that the Blue unit breaks lock of it. Once the Blue UAV stops monitoring the enemy target, it sails towards other unidentified contacts or, if there is none, along its patrol route. To avoid engaging on the same target with other friendly forces, the Squad Friendly Awareness has been set to -100. Finally, the Blue UAV is equipped with a detecting sensor. In this study the Advanced Sensor Model is used. The detection range has been divided into five zones, and each one has different detection probability. The same method is applied for the Classification Probabilities. Finally, when a Blue UAV identifies a target, it "refuels" it with a rate of one fuel unit per time step. At the end of each simulation run, the remaining "fuel" is used to calculate the time a target was monitored.

c.   Blue Ground Radars

The Blue ground radars have a limited FOV of 270 degrees. This is reasonable because none of the current ground radars in the Aegean Sea has a peripheral "visible" sector. They send all the information about the targets detected to the Blue Operational Centre. They also provide information to the available UAVs. The Advanced Mode for the sensors is used. The maximum detection and classification ranges are subdivided into five zones, and each one has different probability of detection/classification. This captures the intuitive opinion that if a contact is closer to the radar, it has more chances to be detected. While the radar has a contact under positive identification, it "refuels" it, and this helps us to keep track of the time the contact is classified.

d. Blue Operational Centre

The role of the Blue Operational Centre is to gather the information from the Blue sensors and send them to the Blue ship (Squad 1) and Blue UAV (Squad 7) (Figure 24). The Operational Centre does not have detection capabilities itself. In reality, it can be located either away from the AOI or onboard a Command ship.
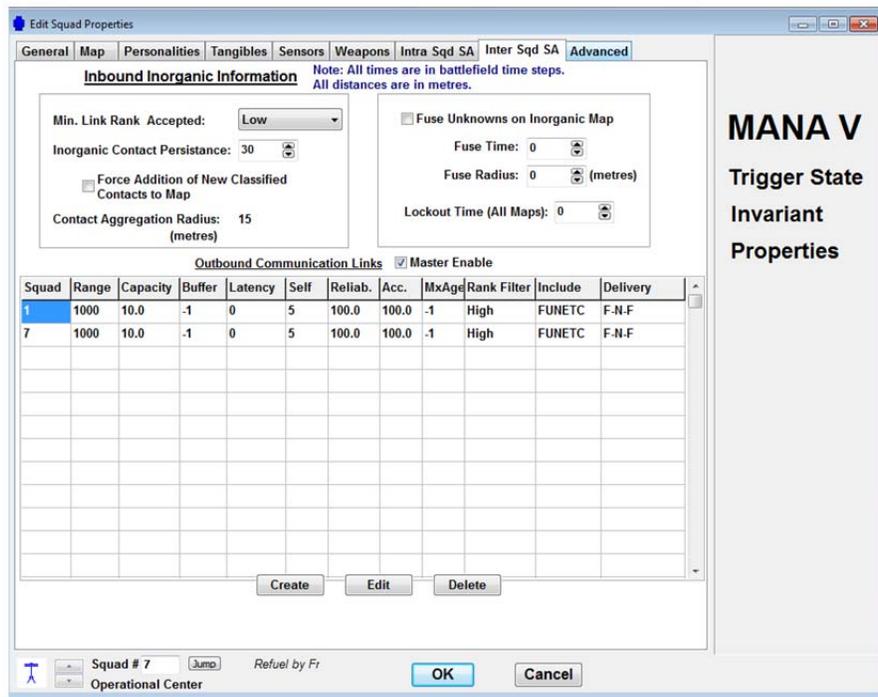
Figure 24. Inter squad SA table of the Blue Operational Centre.

e. Red Ships

In every model there are four Red ships. Depending on the model, they have different tactics. In the "Open Sea" model, they approach the closest merchant vessel and stay close to it for more than 2.5 hours (10,000 time steps) while transiting the open sea. During this tactic, they increase their concealment in order to avoid detection by the Blue surveillance system. In the "Many Islands" model, the Red ships prefer to stay close to the shoreline in order to reach their final destination. Again, using this tactic, they increase their concealment.

When the Red ships have been identified, they shift to the "Shot At" state and become invisible allowing the Blue UAV/ships to move to the next unidentified contact. They stay in this state for 30 minutes (1800 time steps), where they are considered as identified. Operationally, this is reasonable because in such a short time it is extremely difficult to mislead the surveillance system and avoid the detection. While the vessels are under positive identification, they consume "fuel," and this helps us to keep track of the time the contact is classified. They do not have communication and weapon capabilities. They are equipped with a detection sensor operating in Simple Mode (cookie-cutter), as depicted in Figure 25.
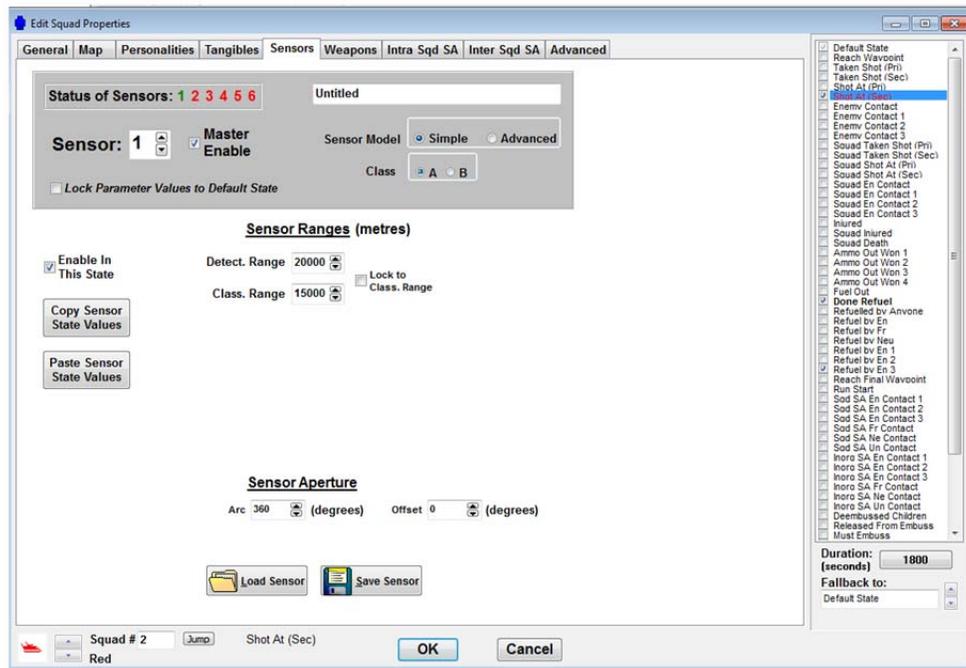
Figure 25. Sensors tab of the Red ship agent.

f.   *Merchant Vessels*

Merchant vessels are randomly distributed in the AOI. Their routes are consistent with the real merchant shipping lanes in the Aegean Sea. They do not have communication and weapon capabilities. Once they are classified by

the Blue sensors, they are assumed as such for the next hour. For this time period, they shift to the "Refuel by Friend" state and increase their concealment to 100 percent. That makes them invisible allowing the Blue Ship/UAV to move to the next unidentified contact. When the one-hour period expires, they have to be revisited in order to be re-identified. Operationally this is reasonable because merchant vessels usually keep constant speed and heading, and this fact facilitates the users of the surveillance sensors to keep track of them. While the vessels are under positive identification, they consume "fuel," and this helps us to keep track of the time the contact is classified.

g. Fishing Vessels

Fishing vessels are randomly distributed in the AOI. They remain constant throughout the scenarios. They do not have communication and weapon capabilities. Once they are classified by the Blue sensors, they are assumed as such for the next two hours. For this time period, they shift to the "Refuel by Friend" state and increase their concealment to 100 percent. That makes them invisible allowing the Blue Ship/UAV move to the next unidentified contact. When the two-hour period expires, they have to be revisited in order to be re-identified. Operationally this is reasonable because fishing vessels remain approximately at the same position for long periods of time without trying to mislead the surveillance system. While the vessels are under positive identification, they consume "fuel," and this helps us to keep track of the time the contact is classified.

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IV. DESIGN OF EXPERIMENT

A. EXPERIMENTAL SETUP AND FACTORS

This section provides a brief description of the experimental setup that is followed in this study. Additionally, the factors that are varied in the Design of Experiment (DOE), along with their ranges, are presented.

1. Experimental Setup

In this study, two different scenarios are studied. The first is the "Open Sea" scenario in which the enemies have to transit long distances without the coverage of nearby islands to reach their final destination. This scenario represents the situation in the Northern and Southern Aegean Sea. The second scenario, which is found in the Central and Southeast Aegean Sea, is called "Many Islands" because it is characterized by a large number of islands being close to each other. The Red ships try to take advantage of this situation. The two scenarios are studied separately, and the conclusions of both will shed light on a part or the whole AOI.

The two scenarios explore different combinations of Blue sensors and Red tactics. Concerning the Blue forces, the current surveillance system represented by two ground radars and two surface ships will be contrasted with some proposed solutions. The first solution involves one UAV in addition to the current system. In the second solution, two UAVs support the operations of the current surveillance system. The last solution is more challenging since the use of two UAVs along with two ground radars is being studied without the support of surface ships.

From the enemy's perspective, two tactics are studied. When the Red ships aim to reach a destination without having the option to sail close to nearby islands, they approach transiting merchant vessels and keep close to them, as much as they can. This tactic is captured into the "Open Sea" scenario. In contrast, when the environment is characterized by many islands in close

distances, the Red ships try to take advantage of the islands. Sailing near to the shoreline, they try to avoid being detected by the adversary's sensors. This situation is captured in the "Many Islands" scenario. A combination, or further investigation, of the enemy's tactics is not part of this thesis. The experimental setup just described is shown in Table 11.

Table 11.   Experiment setup.

	"Open Sea" Scenario	"Many Islands" Scenario
Blue Sensors Combinations	no UAV	no UAV
	1 UAV	1 UAV
	2 UAVs	2 UAVs
	no ships/ 2UAVs	no ships/ 2UAVs
Red Tactics	Approach merchant vessels	Approach shoreline

2.   Design Factors

In every experiment, it is impossible to account for every factor that might affect the outcome. Investigating too many factors would make the analysis extremely difficult, whereas having too few factors might result in inaccurate conclusions. This study varies 21 factors (Table 12) that seem to have the most important impact on the performance of the surveillance system. The factors were chosen based on opinions of subject matter experts, as well as the author's experience. Although in simulation experiments all the factors are manipulated, in reality this is not the case. For this reason, the factors are distinguished into controllable and uncontrollable (Sanchez & Wan, 2012).

Table 12.   Independent factors varied in the DOE.

	Platform	Variable	Type	Unit	Range
1.	UAV	Speed	Continuous (sampled in discrete values)	knots	70-150
2.		Max Detection Range	Continuous	meters	5000-30000
3.		Avg. Time Between Detections (Max range)	Continuous	seconds	5-120
4.		Probability of Classification at Min Range	Continuous	0.7	1
5.		Communication Latency	Continuous	seconds	30-120
6.		Communication Accuracy	Continuous	percentage	50-100
7.	Blue Ships	Speed	Continuous (sampled in discrete values)	knots	15-25
8.		Max Detection Range	Continuous	meters	5000-25000
9.		Avg. Time Between Detections (Max range)	Continuous	seconds	8- 240
10.		Probability of Classification at Min Range	Continuous	0.7	1
11.	Blue Ground Radars	Max Detection Range	Continuous	meters	10000-50000
12.		Avg. Time Between Detections (Max range)	Continuous	seconds	5-120
13.		Probability of Classification at Min Range	Continuous	0.7	1
14.	Operational Centre	Communication Latency	Continuous	seconds	30-120
15.		Communication Accuracy	Continuous	percentage	50-100
16.	Red Ships	Stealth	Continuous	percentage	30-90
17.		Detection Range	Continuous	meters	5000-25000
18.		Speed	Continuous (sampled in discrete values)	knots	15-35
19.	Fishing Vessels	# of fishing vessels	Discrete	-	5-50
20.	Merchant vessels	# of merchant vessels	Discrete	-	4- 30
21.		speed	Continuous (sampled in discrete values)	knots	8-20

The controllable factors are those that are varied at will by the experimenter. All the variables that deal with the Blue sensors (Blue ships, UAVs, ground radars and Operational Centre) fall in this category. These variables describe the detection capabilities of the Blue sensors and possibly have an effect, major or minor, to the response variable. These factors include the detection and classification ranges, the probabilities of detection, speed and communication capabilities.

Uncontrollable or noise factors are those that cannot be manipulated by the decision maker in reality. In this experiment, the number of merchant or fishing vessels, their speed and the configurations of the Red ships fall into this category. They may or may not have a significant effect on the outcome, but by varying within valid ranges, they introduce a natural variability in the models. In that way more accurate conclusions are drawn.

In addition to the 21 independent variables that we explicitly vary in the DOE, there are an additional 52 variables that depend on one of the aforementioned factors. These variables describe the sensors' capabilities, and this technique is extremely useful when the Advanced Detection Mode is used (see Chapter III).

The Maximum Classification Range is set to 0.8* Maximum Detection Range for all the agents. Moreover, all the Blue units use the Advanced Detection Mode where a range table can be set up to define how the sensing capability falls off with increased distance. Therefore, their detecting ranges are divided into five homocentric cycles, each one with a different chance to detect (or classify) a target. The "upper" range value for each of the four inner cycles is calculated by multiplying the maximum detection (or classification) range by 1/5, 2/5, 3/5 and 4/5, respectively. For example, if the maximum detection range is 25,000 meters, Zone 1 will be up to 5,000 meters, Zone 2 from 5,000 to 10,000 meters, etc.

For the detection, those "zones" are associated with Average Times between Detections. As indicated in the previous paragraph, these times are calculated by multiplying the Average Times between Detections for the maximum detection (or classification) range by 1/5, 2/5, 3/5 and 4/5, respectively.

For the classification, the five ranges are assigned with probabilities of classification. In this case, taking as a reference the first zone, which has the maximum probability of classification, we calculate the rest by multiplying successively by 0.9, 0.8, 0.7 and 0.6. In that way, at the verge of the classification range we obtain 60 percent of the nominal maximum probability of classification. All the dependent variables are depicted in Table 13.

Table 13.   Dependent variables in the DOE

		Dependent Variable	Associated Independent Variable	Multiplying by
1.		Maximum Classification Range (Zone 5)	Maximum Detection Range (Zone 5)	0.8
2.		1st detection range (Zone 1)	Maximum Detection Range (Zone 5)	0.2
3.		2nd detection range (Zone 2)		0.4
4.		3rd detection range (Zone 3)		0.6
5.		4th detection range (Zone 4)		0.8
6.		Time Between Detections (Zone 1)	Time Between Detections IN Maximum Range (Zone 5)	0.2
7.		Time Between Detections (Zone 2)		0.4
8.		Time Between Detections (Zone 3)		0.6
9.	UAV	Time Between Detections (Zone 4)		0.8
10.		1st classification range (Zone 1)	Maximum Classification Range (Zone 5)* (* it is also dependent)	0.2
11.		2nd classification range (Zone 2)		0.4
12.		3rd classification range (Zone 3)		0.6
13.		4th classification range (Zone 4)		0.8
14.		Probability of Classification (Zone 2)	Probability of Classification at Min Range (Zone 1)	0.9
15.		Probability of Classification (Zone 3)		0.8
16.		Probability of Classification (Zone 4)		0.7
17.		Probability of Classification (Zone 5)		0.6
18.		Maximum Classification Range (Zone 5)	Maximum Detection Range (Zone 5)	0.8
19.		1st detection range (Zone 1)	Maximum Detection Range (Zone 5)	0.2
20.		2nd detection range (Zone 2)		0.4
21.		3rd detection range (Zone 3)		0.6
22.		4th detection range (Zone 4)		0.8
23.		Time Between Detections (Zone 1)	Time Between Detections IN Maximum Range (Zone 5)	0.2
24.		Time Between Detections (Zone 2)		0.4
25.		Time Between Detections (Zone 3)		0.6
26.	Blue Ships	Time Between Detections (Zone 4)		0.8
27.		1st classification range (Zone 1)	Maximum Classification Range (Zone 5)* (* it is also dependent)	0.2
28.		2nd classification range (Zone 2)		0.4
29.		3rd classification range (Zone 3)		0.6
30.		4th classification range (Zone 4)		0.8
31.		Probability of Classification (Zone 2)	Probability of Classification at Min Range (Zone 1)	0.9
32.		Probability of Classification (Zone 3)		0.8
33.		Probability of Classification (Zone 4)		0.7
34.		Probability of Classification (Zone 5)		0.6
35.		Maximum Classification Range (Zone 5)	Maximum Detection Range (Zone 5)	0.8
36.	Ground Radars	1st detection range (Zone 1)	Maximum Detection Range (Zone 5)	0.2
37.		2nd detection range (Zone 2)		0.4

38.		3rd detection range (Zone 3)		0.6
39.		4th detection range (Zone 4)		0.8
40.		Time Between Detections (Zone 1)	Time Between Detections IN Maximum Range (Zone 5)	0.2
41.		Time Between Detections (Zone 2)		0.4
42.		Time Between Detections (Zone 3)		0.6
43.		Time Between Detections (Zone 4)		0.8
44.		1st classification range (Zone 1)	Maximum Classification Range (Zone 5)* (* it is also dependent)	0.2
45.		2nd classification range (Zone 2)		0.4
46.		3rd classification range (Zone 3)		0.6
47.		4th classification range (Zone 4)		0.8
48.		Probability of Classification (Zone 2)	Probability of Classification at Min Range (Zone 1)	0.9
49.		Probability of Classification (Zone 3)		0.8
50.		Probability of Classification (Zone 4)		0.7
51.		Probability of Classification (Zone 5)		0.6
52.	Red Ships	Maximum Classification Range	Maximum Detection Range	0.8

B.   NEARLY ORTHOGONAL LATIN HYPERQUBE DESIGNS

Latin Hypercubes (LH) have been increasingly popular in the designs of computer experiments because they provide a flexible way of constructing efficient designs to explore quantitative factors. They have "some of the space-filling properties of factorial designs with fine grids but require orders of magnitude less sampling" (Sanchez & Wan, 2011). If we had a small number of factors, we could create a full factorial design to study all possible combinations of the factor levels. However, this is impossible when we deal with a large number of input variables because the time needed would increase geometrically.

Nearly Orthogonal Latin Hypercubes (NOLH) are "LH which have good space-filling and orthogonality properties for a small or moderate number of factors. These designs are not square, but the number of design points is radically fewer than the numbers for the gridded designs" (Sanchez & Wan, 2011).

Cioppa and Lucas (2007, pp. 45–55) presented NOLH with good space-filling properties for up to 22 factors in as few as 129 input combinations, and later up to 29 factors in 257 design points. An Excel spreadsheet, developed

from the Simulation Experiments and Efficient Design (SEED) Center for Data Farming at the Naval Postgraduate School in Monterey, is used to create those specific combinations that the NOLH design demands, as shown in Figure 26.

	UAV_Speed	UAV_MaxDetRan	UAV_AvgTimeBw	UAV_PrClass	UAV_CommsLate	UAV_CommsAcc	BlueShips_Speed	BlueShips_MaxDe	BlueShips_AvgTi	BlueShips_PrClas	BlueShips_Comm	BlueShips_Comm	Radar_MaxDetRa	Radar_AvgTimeB	Radar_ProbClass	OpCentre_Commi	OpsCentre_Comm	Red_Stealth	Red_DetRange
low level	70	5000	5	0.7	30	50	15	5000	8	0.7	30	50	10000	5	0.7	30	50	30	5000
high level	150	30000	120	1	120	100	30	25000	140	1	120	100	50000	120	1	120	100	90	25000
decimals	0	0	0	2	0	0	0	0	0	2	0	0	0	0	2	0	0	0	0
	102	27070	73	0.88	87	95	30	22500	33	0.72	51	69	12500	26	0.8	66	72	34	5703
	79	14961	102	0.99	95	77	30	21875	80	0.88	86	87	50000	107	0.85	32	53	38	5078
	83	19844	18	0.87	116	91	29	22813	93	0.81	48	62	15156	22	0.98	105	78	86	21875
	103	9004	51	0.89	96	87	28	23984	28	0.86	114	89	48594	115	0.89	82	89	90	20547
	99	18965	76	0.82	114	90	26	18750	17	0.94	38	53	22813	14	0.85	44	57	37	10547
	105	14180	115	0.75	108	95	26	24063	103	0.84	106	88	43594	86	0.97	68	69	56	12422
	73	20332	56	0.74	76	76	26	16719	97	0.88	30	63	22344	42	0.74	112	96	70	24609
	101	6074	47	0.82	113	87	25	18594	72	0.72	72	77	42344	80	0.83	112	87	80	17266
	76	17891	112	0.89	65	89	26	24609	31	0.81	115	62	28281	54	0.76	89	70	48	11797
	109	6855	104	0.92	34	80	23	16016	134	0.93	66	84	40313	114	0.74	80	72	37	10078
	81	28242	61	0.99	70	75	30	16953	127	0.79	88	61	18438	51	0.89	39	88	61	15547
	76	8418	14	0.92	63	83	27	17422	73	1	69	75	49219	78	0.92	69	80	78	21719
	92	29023	77	0.72	67	90	25	18281	57	0.98	99	60	11719	59	0.94	90	63	35	9063
	73	11738	88	0.74	44	90	30	15234	102	0.75	62	89	36875	81	0.88	108	71	51	11172
	93	20723	9	0.85	41	76	26	16250	105	0.99	81	63	11875	22	0.73	57	92	87	15859
	100	12031	36	0.72	66	86	29	22109	22	0.85	31	76	40938	71	0.75	63	85	74	16172
	92	18184	97	0.94	111	69	25	18203	29	0.81	76	83	14844	43	0.8	60	91	39	7188
	108	11934	97	0.88	78	64	28	18516	110	0.94	112	62	34375	77	0.84	45	94	41	8047
	86	24922	59	0.85	103	52	28	20781	97	0.77	52	86	16250	16	0.91	77	69	76	19766
	86	9980	37	0.9	97	63	27	23359	69	0.83	102	51	44219	98	0.93	106	64	73	16328
	97	17598	95	0.76	101	54	30	24297	58	0.92	32	90	14375	24	0.98	57	96	35	13203
	110	13301	75	0.76	112	57	28	21484	109	0.74	97	52	47969	118	0.85	55	71	45	9922
	101	24629	62	0.84	77	74	27	19531	99	0.92	50	95	16875	46	0.79	119	55	83	22109
	87	14766	43	0.78	97	54	27	18125	71	0.82	74	75	39375	90	0.78	91	50	88	23750
	91	17988	96	0.97	49	69	23	24922	17	0.85	86	92	21719	11	0.82	99	88	49	14375
	108	11445	109	0.86	65	52	25	22734	108	0.97	49	63	29375	116	0.79	76	76	54	7578
	78	24824	60	0.94	75	72	24	21172	103	0.77	90	78	21563	58	0.87	68	56	75	23438

readme / gbl / NOLH for up to 7 factors / NOLH for up to 11 factors / NOLH for up to 16 factors / NOLH for 17-22 factors / NOLH for up to 29 factors / Sheet1

Figure 26. Snapshot of the spreadsheet used for the DOE.

There are three major benefits of NOLH in this study:

- Only 257 design points are necessary in this DOE. Instead, if we wanted to explore the 23 factors as 2-level, and not as continuous, we would need more than eight million design points.

- It is a good space-filling design because "the design points are scattered throughout the experimental region with minimal unsampled regions" (Cioppa & Lucas, 2007). Figure 27 is a scatterplot matrix that depicts the projections of the full design onto each pair of factors. It can be easily seen that this property holds.

Figure 27. Scatterplot Matrix for all the factors in the DOE.

- Near orthogonality ensures that all correlations between the factors are very small, between the interval (-0.03, 0.03). Figure 28 confirms this property for the first ten factors because the maximum absolute pairwise correlation is 0.0096.

Correlations	UAV_Speed	UAV_MaxDetRange	UAV_AvgTimeBweenDet	UAV_PrClass	UAV_CommsLatency	UAV_CommsAccuracy	BlueShips_Speed	BlueShips_MaxDetRange	BlueShips_AvgTimeBweenDet	BlueShips_PrClass
UAV_Speed	1.0000	0.0002	-0.0010	0.0009	-0.0004	0.0023	0.0052	0.0005	-0.0017	-0.0029
UAV_MaxDetRange	0.0002	1.0000	-0.0007	-0.0058	0.0009	0.0021	0.0045	0.0000	0.0009	-0.0007
UAV_AvgTimeBweenDet	-0.0010	-0.0007	1.0000	0.0003	0.0019	0.0025	0.0051	-0.0006	-0.0037	0.0032
UAV_PrClass	0.0009	-0.0058	0.0003	1.0000	0.0044	0.0057	0.0168	-0.0028	0.0023	-0.0084
UAV_CommsLatency	-0.0004	0.0009	0.0019	0.0044	1.0000	0.0046	-0.0034	0.0031	0.0002	0.0020
UAV_CommsAccuracy	0.0023	0.0021	0.0025	0.0057	0.0046	1.0000	-0.0069	-0.0015	-0.0003	-0.0095
BlueShips_Speed	0.0052	0.0045	0.0051	0.0168	-0.0034	-0.0069	1.0000	0.0078	-0.0053	-0.0005
BlueShips_MaxDetRange	0.0005	0.0000	-0.0006	-0.0028	0.0031	-0.0015	0.0078	1.0000	0.0007	-0.0039
BlueShips_AvgTimeBweenDet	-0.0017	0.0009	-0.0037	0.0023	0.0002	-0.0003	-0.0053	0.0007	1.0000	-0.0018
BlueShips_PrClass	-0.0029	-0.0007	0.0032	-0.0084	0.0020	-0.0095	-0.0005	-0.0039	-0.0018	1.0000
BlueShips_CommsLatency	-0.0013	-0.0018	0.0008	0.0016	-0.0010	-0.0035	-0.0084	-0.0036	-0.0003	-0.0052
BlueShips_CommsAccuracy	-0.0007	-0.0006	0.0020	-0.0003	-0.0015	-0.0022	0.0048	-0.0009	0.0006	-0.0038
Radar_MaxDetRange	-0.0010	-0.0006	0.0002	-0.0005	-0.0004	-0.0039	-0.0053	0.0002	-0.0001	-0.0017
Radar_AvgTimeBweenDet	0.0023	-0.0014	-0.0020	0.0011	0.0006	-0.0028	0.0005	0.0010	0.0007	-0.0027
Radar_ProbClass	0.0042	0.0044	0.0026	-0.0073	0.0056	-0.0039	0.0100	-0.0012	0.0005	0.0003
OpCentre_CommsLatency	0.0013	0.0030	0.0003	-0.0055	-0.0055	-0.0005	-0.0012	-0.0010	0.0006	-0.0013
OpsCentre_CommsAccuracy	-0.0007	0.0008	-0.0003	-0.0022	-0.0023	-0.0033	-0.0045	-0.0010	0.0030	0.0027
Red_Stealth	-0.0023	0.0008	0.0013	-0.0008	-0.0039	-0.0012	-0.0092	0.0001	0.0034	-0.0013
Red_DetRange	-0.0010	0.0003	0.0007	0.0030	0.0002	0.0004	-0.0020	-0.0001	-0.0004	-0.0007
Red_Speed	0.0048	-0.0043	0.0009	-0.0035	-0.0056	-0.0003	-0.0080	0.0026	-0.0041	0.0050
NumberFishVessels	-0.0040	0.0027	-0.0016	-0.0010	0.0038	-0.0059	0.0035	-0.0014	0.0008	0.0049
NumberMerchVessels	-0.0033	-0.0013	-0.0038	-0.0045	0.0016	-0.0028	0.0001	0.0029	0.0076	-0.0005
MerchVessels_Speed	0.0050	0.0050	-0.0100	-0.0095	-0.0076	0.0026	-0.0015	-0.0076	-0.0008	-0.0068

Figure 28. Snapshot of correlation matrix for the first ten factors of the DOE.

C. EXPERIMENT EXECUTION

Our simulation experiment was run on a high-performance cluster with 44 processors, called "Reaper." The software packages xStudy, OldMcData and Condor were used in this study to generate the data files. XStudy, written by SEED Center Research Associate Steve Upton, is a graphical user interface for generating a study design file in .xml format. Among other information, it identifies the model used, the number of replications, initial random seeds and what variables will be used for variation. It is also used to map each factor of the DOE to a specific element of the MANA scenario file.

OldMcData (OMD) is a software application designed to do data farming runs, from running large simulation experiments on a distributed computer cluster to multiple replications of a single excursion on a single machine. For runs on a distributed computing cluster, OMD uses Condor, an open-source distributed computing environment, to handle the scheduling and managing of the active

jobs. All the software mentioned in the previous paragraphs is available through the NPS SEED Centre's website (http://harvest.nps.edu/).

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V. RESULTS AND DATA ANALYSIS

A. MEASURES OF EFFECTIVENESS AND DATA PREPARATION

This section describes the calculation made to obtain the two MOEs and the reasons that led us to manipulate the data taken for the 1-UAV case. Additionally, this section contains our study about the necessary assumptions that have to be met to conduct parametric statistical methods.

1. Measures of Effectiveness

As illustrated in Chapter III, two Measures of Effectiveness (MOE) are used. The first is "The proportion of time the enemy ships are positively identified." This MOE, referred to as MOE 1, estimates how the surveillance system of the Blue Force performs. This measure is indirectly calculated using the amount of "Fuel" of each Red Agent. At the beginning of a run, each one of the four Red ships is equipped with a certain amount of fuel that is set to remain constant any time, unless it is identified by the Blue Force. For the time period the targets are monitored, they consume one unit of fuel per time step. At the end of each simulation run, the fuel that all the Red Ships have consumed is summed up and divided by the number of Red Ships and the Total Run Time. In both the scenarios, there are four Red Ships that try to reach their goal without being detected. Finally, the result of MOE 1 is a number expressed as a percentage. Formula (1) describes the calculation of MOE 1:

$$MOE\,1 = \frac{Sum\,of\,Fuel\,Consumed\,by\,\mathrm{Re}\,d\,Ships}{4*Total\,Run\,Time} \qquad (1)$$

The second MOE, referred to as MOE 2, is "The proportion of time the merchant vessels are positively identified." Although we are mostly interested in the surveillance performance over the Red Ships, this metric is used as an element of force validation to the simulation model. It is expected that the second MOE will be higher in all cases because Merchant Vessels do not use any tactics

to avoid detection from the Blue Force. Additionally, it will be interesting to see to what extent this metric is affected by the various combinations of the Blue Sensors.

The same procedure for MOE 1 is used to calculate MOE 2. Like Red Ships, Merchant Vessels consume "fuel" for the time period they are monitored by the surveillance system. The overall amount of fuel that the Merchant Vessels consumed is divided by the aggregated time they were in the simulation run. Formula (2) describes the calculation of MOE 2:

$$MOE\,2 = \frac{Sum\,of\,Fuel\,Consumed\,by\,Merchant\,Vessels}{k * Total\,Run\,Time}$$

(2)

where k is the number of Merchant Vessels in the model.

The "Open Sea" model involves 16 Merchant Vessels, and the "Many Islands" model involves 10. Again, the result yields a percentage.

2. Data Preparation

Concerning the case when only one UAV is deployed, the preliminary runs showed that the area from where it is launched affects the performance of the UAV, with respect to the MOEs, and consequently, of the whole surveillance system. When two UAVs operate, the AOI is equally divided in two sections and each UAV is assigned in a designated section. However, when only one is available, it covers all the AOI by itself. According to the attributes that have been given to the UAV, it patrols along a particular route until it locates an unknown contact. Then it heads towards it to identify it. As it is easily understood, the more contacts there are close to the launch site, the more the UAV contributes to the surveillance system. That is, if the launch site is close to areas with traffic, the UAV will have more opportunities to locate the targets. Additionally, the targets will be identified earlier. The difference in the MOE 1 with respect to the location of a single UAV launched for the "Open Sea" Model is shown in Figure 29. When the UAV started its deployment from the Northwest, the Surveillance System

detected the Red Ships on average 60.7% of the time (SD=O.057). In contrast, when the UAV started its patrol from Southeast, it scored 56.9% (SD=0.056). An independent sample *t*-test with a two tailed alpha level of .05 indicated that scores were significantly higher for the first case than the second (t(998)= -9.381, p<0.0001). The same issue also occurred in the "Many Islands" model (t(998)= -5.244, p<0.001). More details are provided in Appendix A.
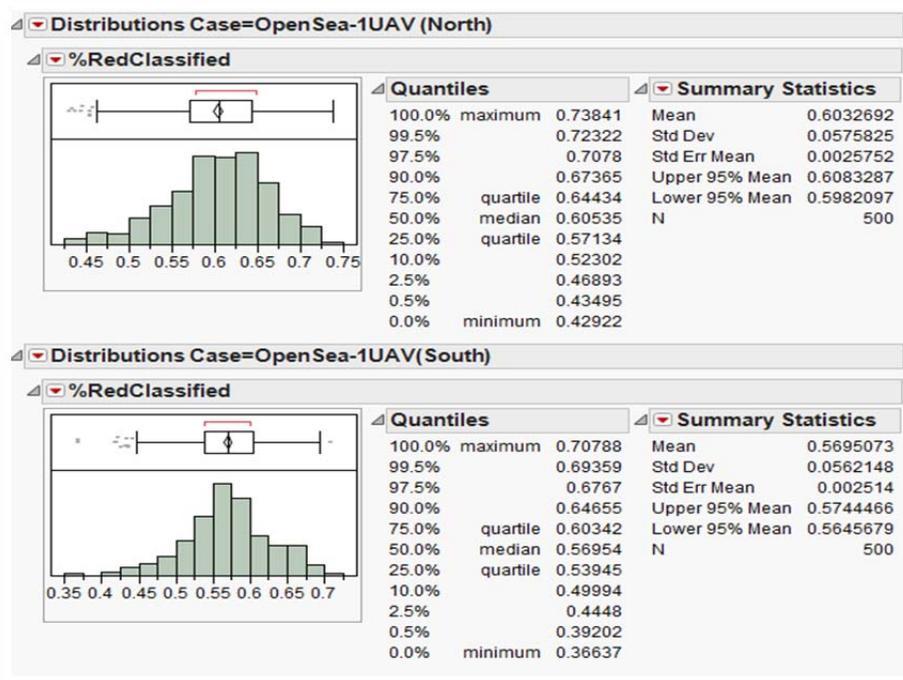
Figure 29. Summary statistics for when a single UAV is launched from Northwest or Southeast in the "Open Sea" model.

In order to mitigate the dissimilarities in geography and target arrangements, two different scenarios were run every time one UAV is needed. In the first scenario, the UAV is launched from a location in the Northwest, whereas in the second, the UAV started its deployment from the Southeast ("Open Sea" model) or the Southwest ("Many Islands" model), respectively. When all the data had been collected, we calculated the averages of the MOEs of the two 1-UAV scenarios. In that way, it can be considered that the UAV was launched from a location in the middle of the true launch sites.

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3.   Assumptions for Statistical Analysis Method

Our decision whether to use parametric or non-parametric method for the analysis is based on whether the assumptions of independence, equality of variance, and normality are met. Below we study those assumptions for the "Open Sea" model.

- Independence of replications: The observations within each treatment group must be independent of one another. Our experiment was completely randomized because we derived our data through a stochastic model. MANA uses a random number generator to randomize the starting positions of agents within their defined home boxes as well as the probabilities of detection. Consequently, scenarios can have considerably different outcomes each time they are run. Therefore, the assumption of independence holds.

- Equality of Variance: The treatments must have approximately equal variances. The side-by-side boxplots for the four cases we are interested in for the "Open Sea" Model are shown in Figure 30. It can be seen that the variance is approximately the same across the different cases. Additionally, because we have a large sample size, we can assume that the equal variance assumption holds.
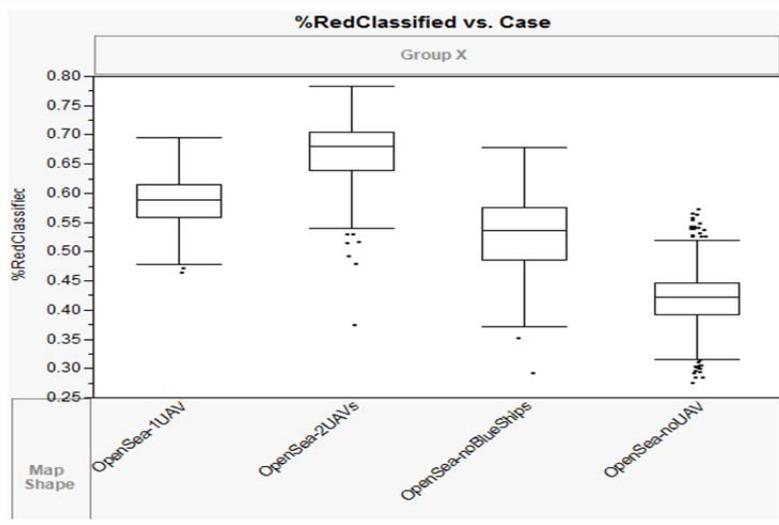
Figure 30. Side-by-side boxplots for the four scenarios in the "Open Sea" model.

- Normal Population: The data of each treatment must come from populations that are Normal or close to Normal. The histograms of

Residuals for the four cases are shown in Figure 31. Although the histogram is skewed on the left in the case where there are no UAVs, it can be considered that all the cases adequately meet the Near Normality Assumption.
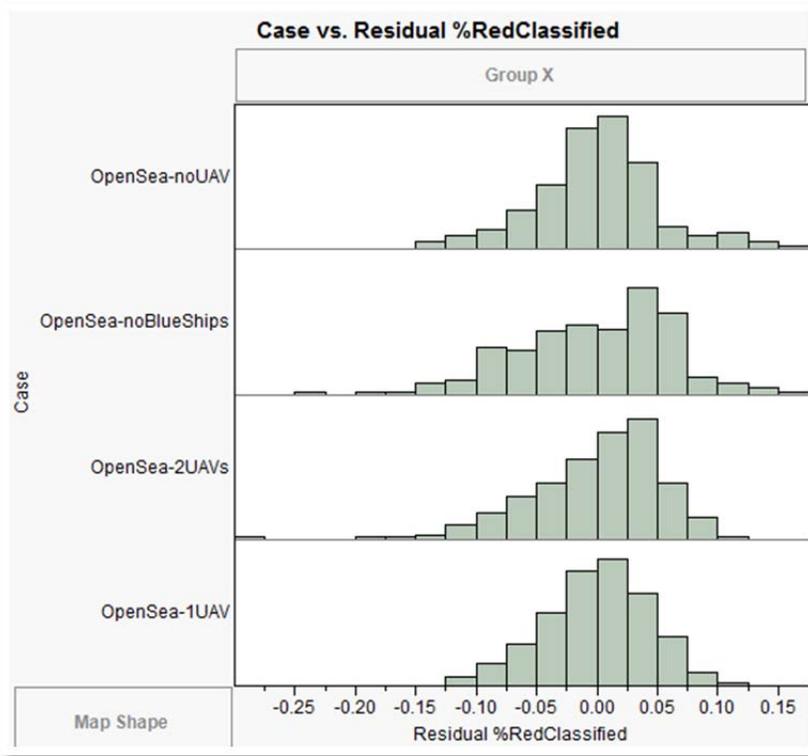
Figure 31. Histogram of the residuals across the four cases in the "Open Sea" model.

The same assumptions also hold for MOE 2 as well as for both MOEs in the "Many Islands" model, as presented in Appendix B. In addition, Appendix C contains the study for the assumptions for both the MOEs for the "Many Islands" Model. Finally, a two-tailed alpha level of .05 was employed for all statistical tests.

B.   RESULTS OF INITIAL RUNS

This section studies the results of 500 initial runs that were conducted for each one of the "Open Sea" and the "Many Islands" models. These runs used a particular configuration of the capabilities of the agents involved in the models.

The results from the simulation were used to compare the performance of the surveillance system in the different scenarios with respect to the MOEs defined earlier. Descriptive statistics of the initial runs are presented and hypotheses for the research questions are tested using appropriate statistical methods. Results from the "Open Sea" model are presented first.

1.   "Open Sea" Model

a.   *Descriptive Statistics*

The distributions of the percentage of Red Ships that had been classified across the four different cases are shown in Figure 32. We notice that on average, the surveillance system yielded the highest numbers of detections when two UAVs operate (Mean= 0.668, SD=0.052). In contrast, the current surveillance system with no UAVs performed the worst (Mean= 0.419, SD=0.049).
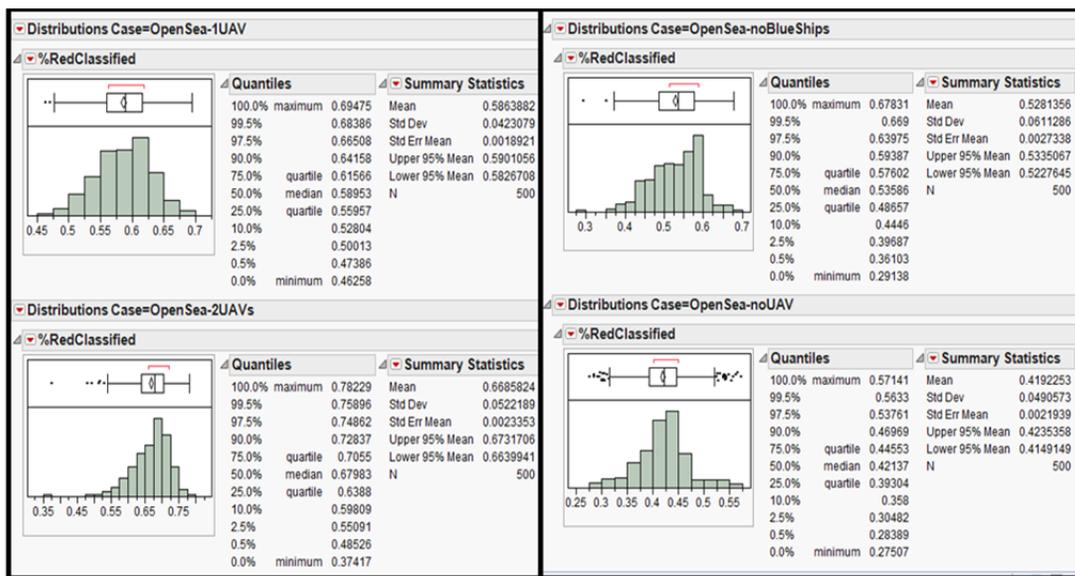
Figure 32. Distributions of MOE 1 for the 500 initial runs across the four cases in the "Open Sea" model.

`The distributions of the percentage of Merchant Vessels that had been classified across the four different cases are shown in Figure 33. As

expected, on average the surveillance system yielded the highest numbers of detections when two UAVs operate (Mean= 0.791, SD=0.033). In contrast, the current surveillance system with no UAVs performed the worst (Mean= 0.477, SD=0.036).
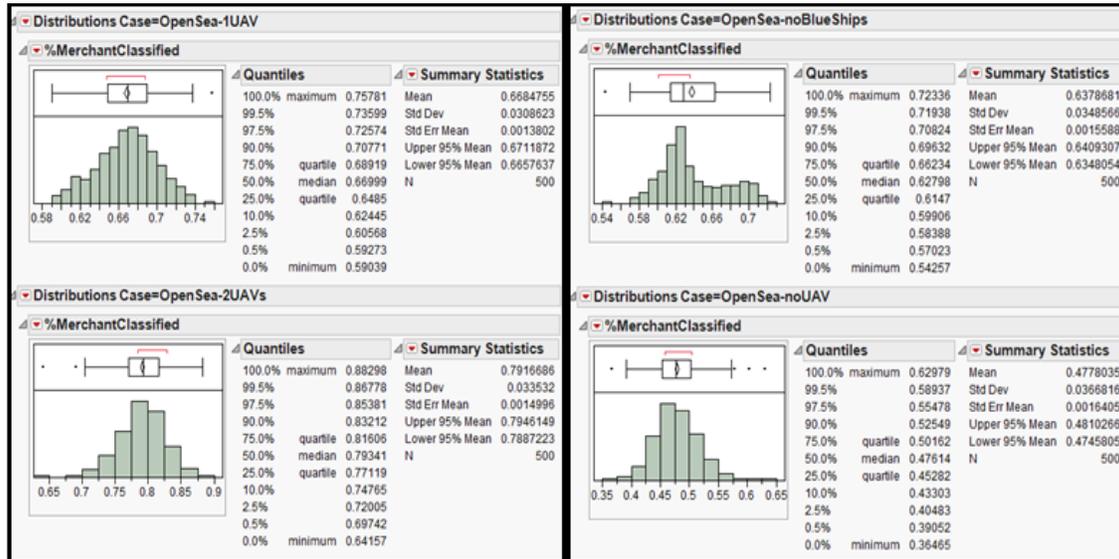
Figure 33. Distributions of MOE 2 for the 500 initial runs across the four cases in the "Open Sea" model.

The average percentage of time the targets are identified is shown in Figure 34. Concerning the Red Ships, besides the best and worst cases which were commented on earlier, the 1-UAV case (which concludes also two Blue Ships) performs slightly better than the case where only two UAVs operate without any surface support.
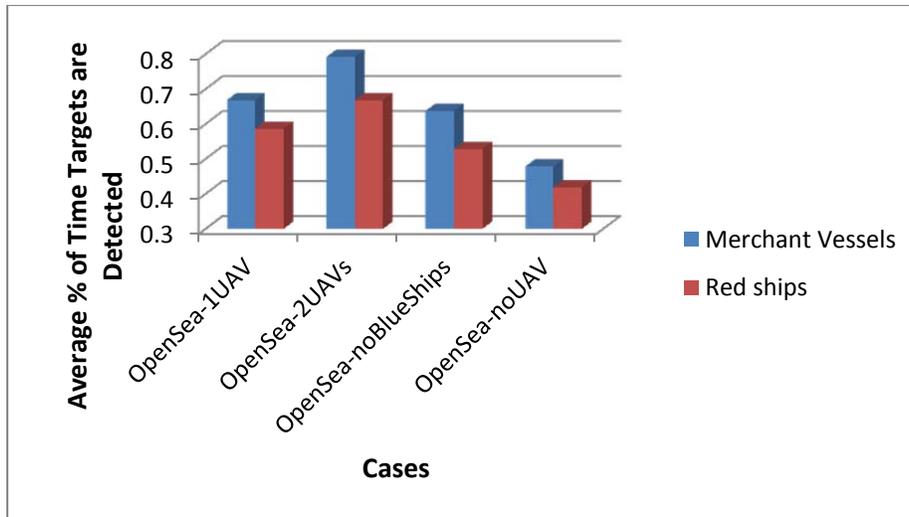
Figure 34. Average percentage of time the targets are detected across the four cases of the "Open Sea" model. (Standard Error ranges from 0.0013 to 0.0027 and would not be easily seen on the bars).

It is worth noting that the Merchant Vessels results are consistent with those of the Red Ships. Additionally, in every case the Red Ships succeed in being detected fewer times than the Merchant Vessels using specific tactics to avoid the adversary sensors. This provides an element of force validation to the simulation model.

b.   Hypotheses Testing

One of the primary questions of this thesis is whether UAVs are able to mitigate the incapability of the current surveillance system to detect targets in complex maritime environments, given that the target's tactic is to approach transiting merchant vessels. In other words, does adding UAVs to a surveillance system that uses traditional units, such as ships and radars, help it become more efficient? The hypothesis tested is:

- H_0: there is no difference in the surveillance system performance whether it uses UAVs or not, given that the target's tactic is to approach transiting merchant vessels ($\mu_1 = \mu_2 = \mu_3 = \mu_4$ where the four populations refer to the four different cases).

- H_A: a surveillance system with UAVs performs better than without UAVs, given that the target's tactic is to approach transiting merchant vessels ($\mu_1 \neq \mu_2 \neq \mu_3 \neq \mu_4$ where the four populations refer to the four different cases).

To test the hypothesis above, Analysis of Variance (ANOVA) was used. This parametric method demands particular assumptions, such as independence of groups, the equal variance assumption and the Normal Population assumption (De Veaux et. al, 2009). In the previous section, we proved that all these assumptions were met for both the MOEs.

The ANOVA (R^2=0.756) showed that the null hypothesis was rejected: there was a significant difference between the four cases (F(3, 1996)=2061.5, $p < 0.001$) (Figure 35). That is, the number of UAVs has a significant effect on the performance of the surveillance system.

Oneway Anova

Summary of Fit

Rsquare	0.75601
Adj Rsquare	0.755643
Root Mean Square Error	0.051624
Mean of Response	0.550583
Observations (or Sum Wgts)	2000

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio	Prob > F
Case	3	16.482292	5.49410	2061.557	<.0001*
Error	1996	5.319387	0.00267		
C. Total	1999	21.801679			
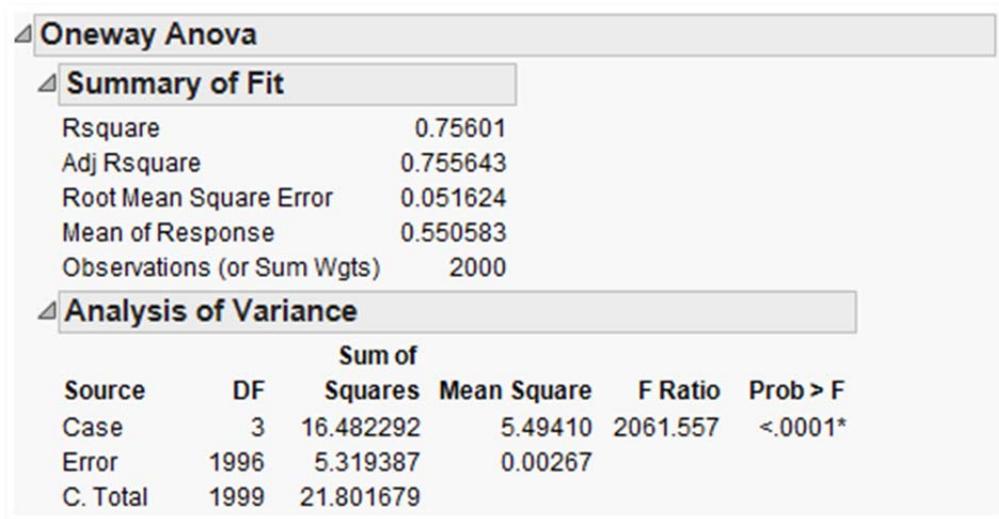
Figure 35. ANOVA for the initial runs of the "Open Sea" model.

To uncover which UAV cases were significantly different from each other, two sample t-tests were conducted in terms of the mean proportion of time Red Ships were positively identified. All the pairwise differences after conducting Student's t-test are shown in Table 14. We notice that, statistically, every case

differs from each other. Furthermore, the largest "improvement" occurs when we go from the current system (no-UAV) to a solution with one or two UAVs.

Table 14.   Ordered pairwise differences report after Student's *t*-test ("Open Sea").

Ordered Differences Report							
Level	- Level	Difference	Std Err Dif	Lower CL	Upper CL	p-Value	
OpenSea-2UAVs	OpenSea-noUAV	0.2493570	0.0032650	0.2429539	0.2557601	<.0001*	
OpenSea-1UAV	OpenSea-noUAV	0.1671629	0.0032650	0.1607598	0.1735660	<.0001*	
OpenSea-2UAVs	OpenSea-noBlueShips	0.1404468	0.0032650	0.1340436	0.1468499	<.0001*	
OpenSea-noBlueShips	OpenSea-noUAV	0.1089103	0.0032650	0.1025071	0.1153134	<.0001*	
OpenSea-2UAVs	OpenSea-1UAV	0.0821941	0.0032650	0.0757910	0.0885973	<.0001*	
OpenSea-1UAV	OpenSea-noBlueShips	0.0582526	0.0032650	0.0518495	0.0646558	<.0001*	

2.   "Many islands" Model

a.   *Descriptive Statistics*

The distributions of the percentage of Red Ships that had been classified across the four different cases are shown in Figure 36. We notice that on average the surveillance system yielded the highest numbers of detections when two UAVs operate (Mean= 0.775, SD=0.036). In contrast, the current surveillance system with no UAVs performed the worst (Mean= 0.480, SD=0.062).
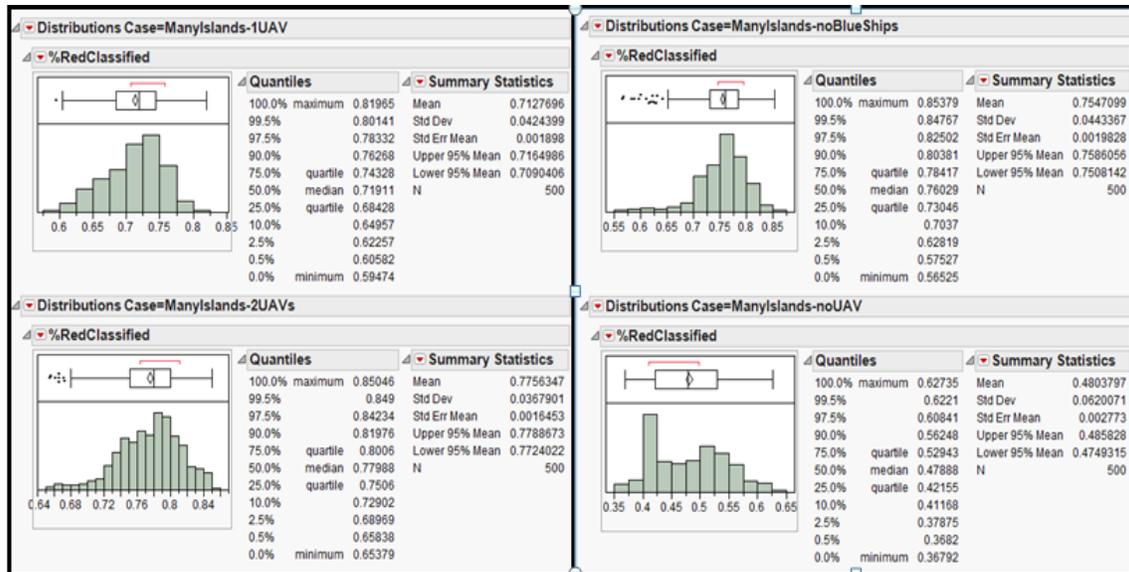
Figure 36. Distributions for MOE 1 for the 500 initial runs across the four cases in the "Many Islands" model.

The distributions of the percentage of Merchant Vessels that had been classified across the four different cases are shown in Figure 37. As expected, on average the surveillance system yielded the highest numbers of detections when two UAVs operate (Mean= 0.914, SD=0.028). In contrast, the current surveillance system with no UAVs performed the worst (Mean= 0.780, SD=0.078).
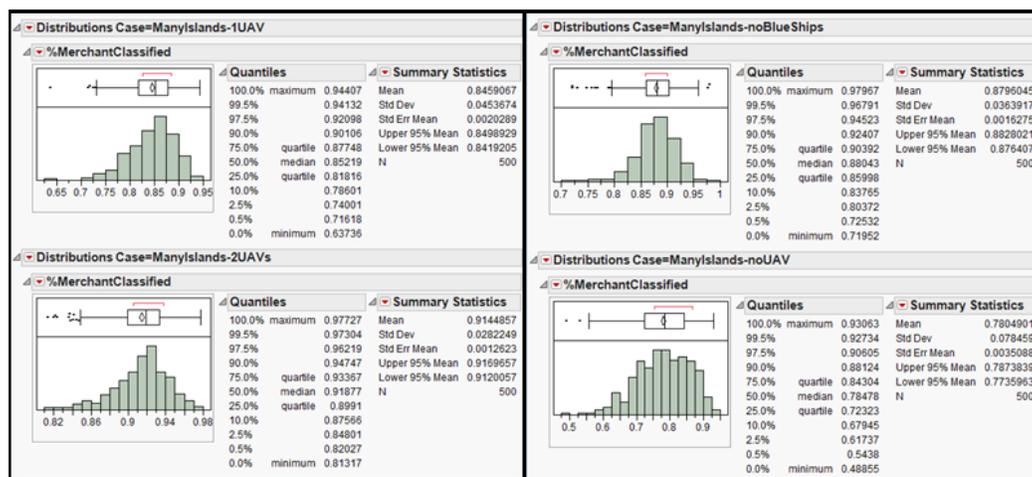

Figure 37. Distributions for MOE 2 for the 500 initial runs across the four cases in the "Many Islands" model.

The average percentage of time the targets were identified is shown in Figure 38. Concerning the Red Ships, there is no big difference whether Blue Ships operate or not, given that two UAVs are deployed. It is worth noticing that the results are consistent for the case of Merchant Vessels, too, because the surveillance system performs similarly as before. Additionally, in every case the Red Ships succeed in being detected fewer times than the Merchant Vessels using specific tactics to avoid the adversary sensors. This set of results provides an element of force validation to the simulation model.
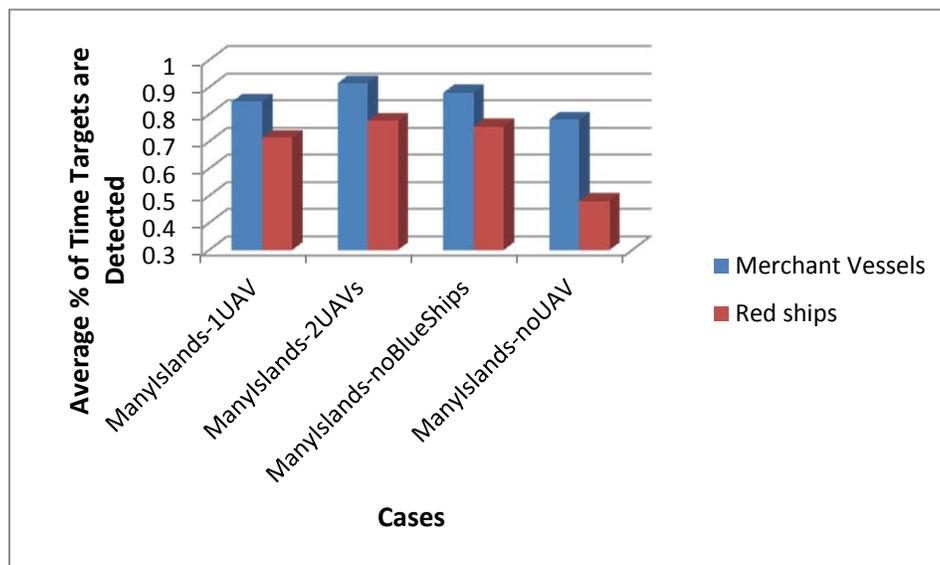
Figure 38. Average percentage of time the targets are detected across the four cases of the "Many Islands" model. (Standard Error ranges from 0.0012 to 0.0035 and would be too small to be easily seen on the bars).

b.   *Hypotheses Testing*

One of the primary questions of this thesis is whether UAVs are able to mitigate the incapability of the current surveillance system to detect targets in complex maritime environments, given that the target's tactic is to take advantage of the nearby shorelines. In other words, whether adding UAVs in a surveillance system that uses traditional units such as ships and radars, it becomes more sufficient. The hypothesis tested is:

- H_0: there is no difference in the surveillance system performance whether it uses UAVs or not, given that the target's tactic is to take advantage of the nearby shorelines ($\mu_1 = \mu_2 = \mu_3 = \mu_4$ where the four populations refer to the four different cases).

- H_A: a surveillance system with UAVs performs better than without UAVs, given that the target's tactic is to take advantage of the nearby shorelines ($\mu_1 \neq \mu_2 \neq \mu_3 \neq \mu_4$ where the four populations refer to the four different cases).

To test the hypothesis above, the Analysis of Variance (ANOVA) was used. This parametric method demands particular assumptions, such as independence of groups, the equal variance assumption and the Normal Population assumption. The study provided in Appendix C proves that the assumptions are met.

Results indicated the null hypothesis was rejected. The ANOVA ($R^2 = 0.861$) showed that there is a significant difference between the four cases ($F_{(3, 1996)} = 4137.9$, p-value < 0.001) (Figure 39). That is, the number of UAVs has significant effect to the performance of the surveillance system.

Oneway Anova

Summary of Fit

Rsquare	0.861483
Adj Rsquare	0.861275
Root Mean Square Error	0.047343
Mean of Response	0.680873
Observations (or Sum Wgts)	2000

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio	Prob > F
Case	3	27.823305	9.27444	4137.935	<.0001*
Error	1996	4.473674	0.00224		
C. Total	1999	32.296979			

Figure 39.   ANOVA for the initial runs of the "Many Islands" model.

To determine which UAV cases were significantly different from each other in terms of the mean proportion of time that Red Ships are positively identified, multiple comparisons methods were employed (two sample t tests). All the pairwise differences after conducting Student's t-test are shown in Table 15. We notice that, statistically, every case differs from each other. Furthermore, the largest "improvement" occurs when we go from the current system (no-UAV) to a solution with one or even two UAVs.

Table 15.   Ordered pairwise differences report after Student's t-test ("Many Islands").

Level	- Level	Difference	Std Err Dif	Lower CL	Upper CL	p-Value
ManyIslands-2UAVs	ManyIslands-noUAV	0.2952550	0.0029942	0.2893829	0.3011271	<.0001*
ManyIslands-noBlueShips	ManyIslands-noUAV	0.2743301	0.0029942	0.2684580	0.2802022	<.0001*
ManyIslands-1UAV	ManyIslands-noUAV	0.2323898	0.0029942	0.2265177	0.2382619	<.0001*
ManyIslands-2UAVs	ManyIslands-1UAV	0.0628652	0.0029942	0.0569931	0.0687373	<.0001*
ManyIslands-noBlueShips	ManyIslands-1UAV	0.0419403	0.0029942	0.0360682	0.0478124	<.0001*
ManyIslands-2UAVs	ManyIslands-noBlueShips	0.0209248	0.0029942	0.0150527	0.0267969	<.0001*

C.   EXPLORATORY ANALYSIS

The purpose of this analysis is not to predict the time that on average the targets will be identified, but rather to understand the significant factors that affect the surveillance system's ability to detect and identify enemies. For this exploratory analysis, we focused on MOE 1 with one UAV, utilizing Least Squares Regression and Partition Trees analytic methods. These two methods were then compared. This comparison was helpful to recognize the significant factors that contribute most to the response variable, although we expect some similarities between the two methods in terms of their overall importance. Interpretation of results from this comparison will be covered in Chapter VI.

1. "Open Sea" Model

The "Open Sea" model with one UAV (and specifically the northern one), which was created in MANA, used the appropriate DOE that was presented in Chapter V. The 129 design points (DP) replicated 250 times each resulting in 32,250 observations. Instead of using the raw data, we used the mean values of the replicated DP to reduce the calculations and produce more visually efficient displays.

a. *Regression Analysis*

We fitted both linear and non-linear Least Square Regression Models. The advantage of the former is that they can often approximate complex processes adequately. The later can be implemented in broader range of applications and comes to fill the gap when linear regression is incapable of describing complex systems. Additionally, the theory associated with both models is well-developed and capable of producing interpretable predictions and optimizations.

The step-wise method embedded in JMP was the main variable selection strategy because it creates models with good fit to the data using as few predictors as possible. Furthermore, the alpha level, which tests the importance of each one of the predictors included in the model in the presence of the rest, was set to .01 to avoid over-fitting. This procedure is useful in creating parsimonious models (Keymal, 2013).

Finally, the models are compared in terms of R^2 and the number of factors included in the model. R^2 is the proportion of the variability of the response explained by the regression model. In the output that will be presented later, the Adjusted R^2 is also shown. This metric attempts to adjust for inflation in R^2 when the number of observations is small compared to the number of factors. Therefore, in discussing the results, we focus on adjusted R^2.

(1)   Main Effects Model. First, we fitted a model only with main effects using the step-wise method and alpha level of 0.01. Prior to examining the results, we first checked that the assumptions of the model were met. Observing the Residual by Predicted plot, we notice that the errors are not equally scattered across the range of the response variable, which means that the variance is not constant (heteroscedasticity). Although the Residual by Raw plot indicates that the errors are independent of each other, we concluded that the above model did not meet the criteria for hypotheses testing. Both the plots are shown in Figure 40.
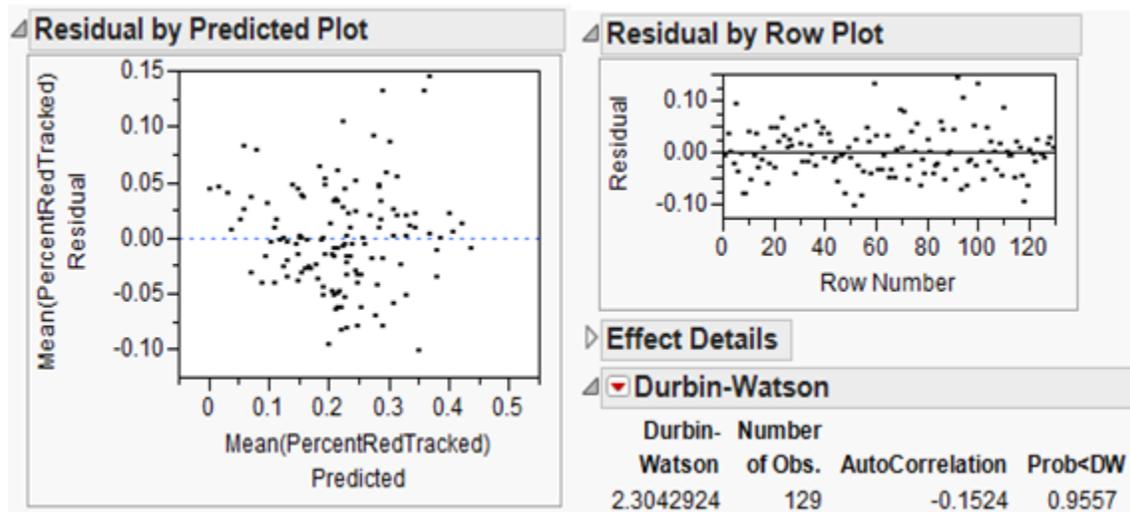
Figure 40. Model diagnostics for the main effects model prior the Box-Cox transformation ("Open Sea").

For that reason we transformed the input data according to Box-Cox result. Figure 41 suggests that we should take the square root of the data instead of the original ones.
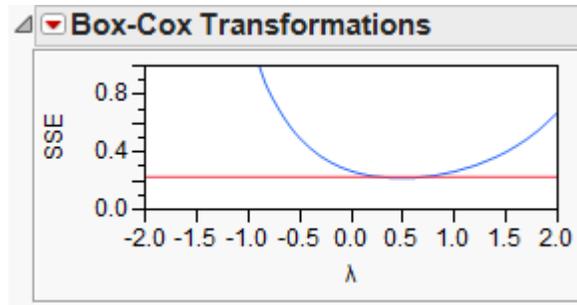
Figure 41. Box-Cox graph that suggests transformation with λ=0.5 ("Open Sea").

Indeed, after the transformation all the model assumptions were met. The Residual by Predicted plot shows constant variance and the Residual by Raw plot along with the large Durbin-Watson p-value (0.771) prove the independence of the observations. Finally, the Normal Quantile plot shows the Normality of the errors (Figure 42).
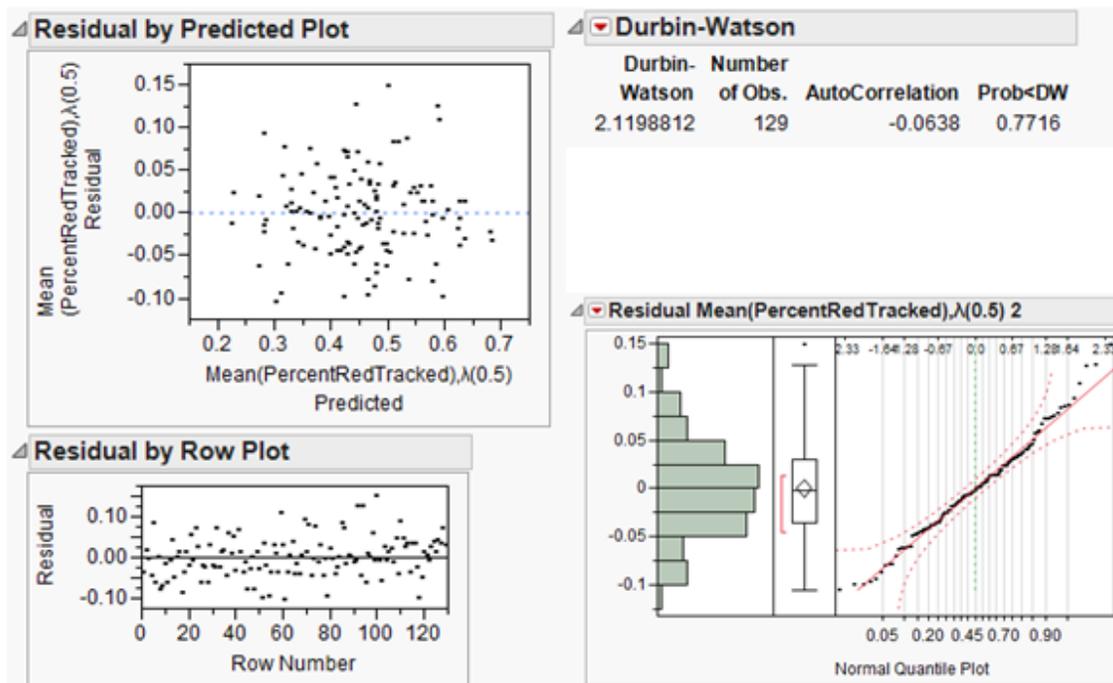
Figure 42. Model diagnostics for the main effects model after the Box-Cox transformation ("Open Sea").

The model we ended up with involves 10 factors and gives *Adjusted* R^2 value of 0.781 (Table 16). The small *p*-value (<0.001) indicates that at least one of the predictors included in the model has great impact on the response.

Table 16.   Statistical results for the main effects model after the Box-Cox transformation ("Open Sea").

Response Mean(PercentRedTracked),λ(0.5)

Summary of Fit

RSquare	0.798401
RSquare Adj	0.781317
Root Mean Square Error	0.051656
Mean of Response	0.454564
Observations (or Sum Wgts)	129

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	10	1.2469639	0.124696	46.7322
Error	118	0.3148619	0.002668	Prob > F
C. Total	128	1.5618257		<.0001*

The factors of the model were sorted in order of significance from high to low (Table 17). The detection ranges of the Blue Sensors seem to be the most significant, followed by the Communication Accuracy of the Operational Centre and the Average Time between Detections of the Blue Radars. The Number and the Speed of Merchant Vessels also have impact to the MOE, along with the Stealth of Red Ships, the Average Time between Detections of the UAV and the Average Time between Detections of the Blue Ships. To give the direction of the impact of each predictor, as the Detection Ranges, the Communication Accuracy and the Speed of the Merchant Vessels increase, the more effective the surveillance system becomes. In contrast, as the Average Time between Detections, the number of Merchant Vessels and the Red Stealth decreases, the surveillance system becomes less effective.

Table 17.   Sorted parameter estimates for the main effects model after the Box-Cox transformation ("Open Sea").

△ **Sorted Parameter Estimates**

Term	Estimate	Std Error	t Ratio		Prob>|t|
Radar_MaxDetRange	4.5688e-6	3.908e-7	11.69		<.0001*
BlueShips_MaxDetRange	8.9862e-6	7.817e-7	11.50		<.0001*
UAV_MaxDetRange	5.5045e-6	6.255e-7	8.80		<.0001*
OpsCentre_CommsAccuracy	0.0021806	0.000313	6.97		<.0001*
Radar_AvgTimeBweenDet	-0.000563	0.000136	-4.15		<.0001*
NumberMerchVessels	-0.002235	0.0006	-3.73		0.0003*
MerchVessels_Speed	0.0048106	0.001294	3.72		0.0003*
Red_Stealth	-0.000875	0.00026	-3.36		0.0010*
UAV_AvgTimeBweenDet	-0.000427	0.000136	-3.14		0.0021*
BlueShips_AvgTimeBweenDet	-0.000195	6.739e-5	-2.90		0.0045*

(2)   Main Effects Model with Interactions. To achieve a better model, we added all the two-way interactions to the previous model. Again we conducted model diagnostics, and the results are shown in Figure 43. It can be easily seen that all the model assumptions are met. The Residual by Predicted plot shows constant variance, and the Residual by Raw plot along with the large Durbin-Watson p-value (0.166) proves the independence of the observations. Finally, the Normal Quantile plot shows the Normality of the errors. No further transformation is needed.
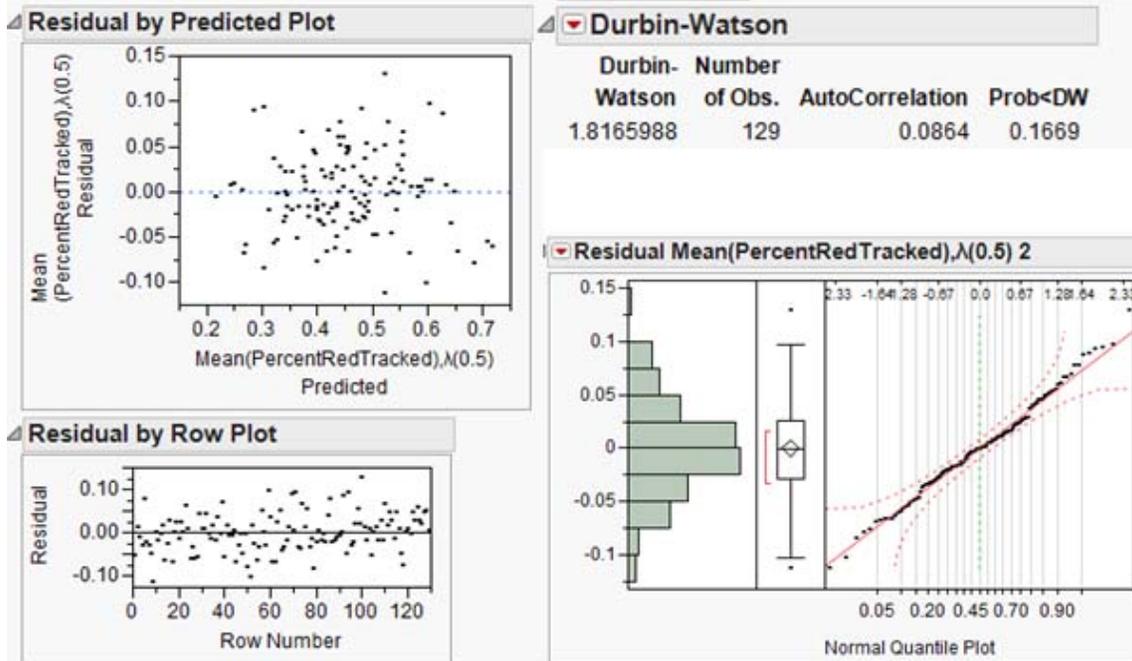
Figure 43. Model diagnostics for the main effects with interactions model ("Open Sea").

The new model contains 13 factors and gives *Adjusted R^2* value of 0.823 (Table 18). The small *p*-value (<0.001) indicates that at least one of the predictors included in the model has great impact to the response.

Table 18.   Statistical results for the main effects model with interactions ("Open Sea").

The factors of the model with interactions were sorted in order of significance from high to low (Table 19). Comparing to the linear model, the eight most significant factors are exactly the same, with the same direction of impact. In addition, this model suggests that the interaction between the Number and the Speed of Merchant Vessels, the Blue Ships' Average Time between

Detections, the interaction between the Blue Radar Range and its Time Between Detections, as well as the interaction between the Blue Radar's Detection Range with its Average Time between Detections have a statistically significant, but to a lesser extent, effect to the response. Finally, the Red Speed affects also the MOE.

Table 19.　　　Sorted parameter estimates for the main effects model with interactions ("Open Sea").

Sorted Parameter Estimates

Term	Estimate	Std Error	t Ratio		Prob>|t|
Radar_MaxDetRange	4.5773e-6	3.508e-7	13.05		<.0001*
BlueShips_MaxDetRange	8.9845e-6	7.017e-7	12.80		<.0001*
UAV_MaxDetRange	5.4965e-6	5.615e-7	9.79		<.0001*
OpsCentre_CommsAccuracy	0.002183	0.000281	7.78		<.0001*
Radar_AvgTimeBweenDet	-0.000571	0.000122	-4.68		<.0001*
MerchVessels_Speed	0.0048516	0.001162	4.18		<.0001*
NumberMerchVessels	-0.002221	0.000538	-4.13		<.0001*
Red_Stealth	-0.000874	0.000234	-3.74		0.0003*
(NumberMerchVessels-17.0078)*(MerchVessels_Speed-14.0155)	0.0005419	0.000145	3.74		0.0003*
UAV_AvgTimeBweenDet	-0.000421	0.000122	-3.45		0.0008*
BlueShips_AvgTimeBweenDet	-0.000196	6.05e-5	-3.24		0.0016*
(Radar_MaxDetRange-30000.2)*(Radar_AvgTimeBweenDet-62.5039)	-3.373e-8	1.069e-8	-3.16		0.0020*
Red_Speed	-0.001973	0.0007	-2.82		0.0057*

　　　　　　(3)　　Model with Quadratic Effects. Finally, we fitted a polynomial model to check whether or not second order factors affect the MOE. Again we conducted model diagnostics, and the results are shown in Figure 44. It can be easily seen that all the model assumptions are met. The Residual by Predicted plot shows constant variance, and the Residual by Raw plot along with the large Durbin-Watson p-value (0.873) proves the independence of the observations. Finally, the Normal Quantile plot shows the Normality of the errors. No further transformation is needed.
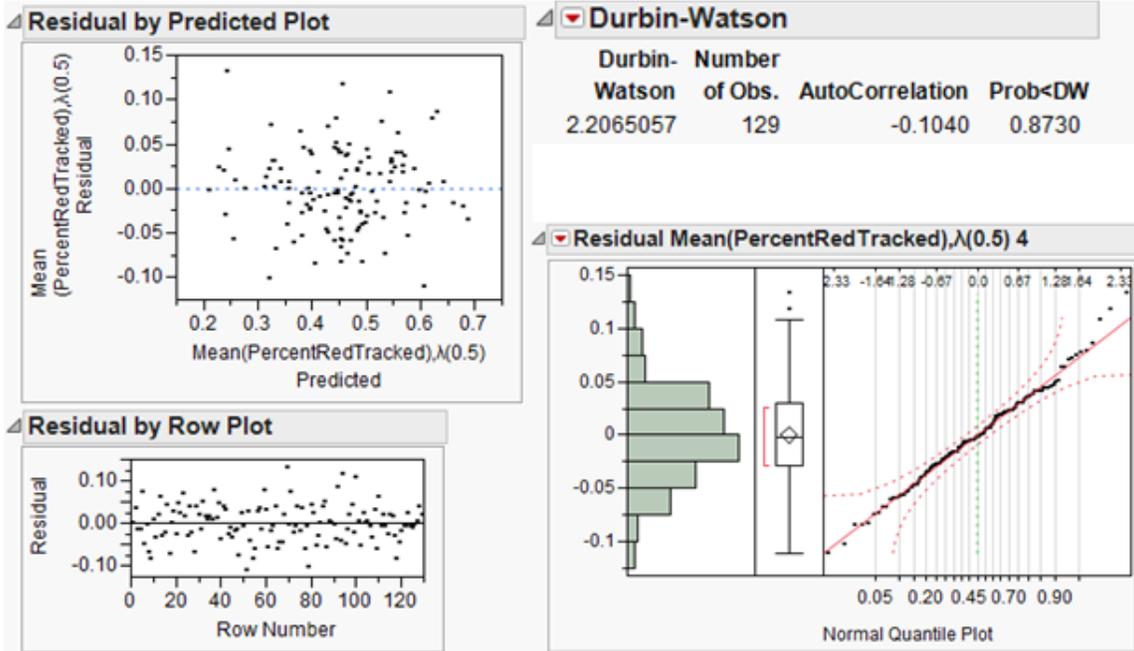
Figure 44. Model diagnostics for the second order model ("Open Sea").

The Second Order model contains 13 factors and gives an Adjusted R^2 value of 0.822 (Table 20). Compared to the previous model, we notice that both of them give similar values of Adjusted R^2 with the same number of terms. The small p-value (<0.001) indicates that at least one of the predictors included in the model has great impact on the response.

Table 20.   Statistical results for the second order model ("Open Sea").

The factors of the Second Order model were sorted in order of significance from high to low (Table 21). Compared to the previous model, we notice that the seven most significant factors are exactly the same. In addition, instead of the two interaction terms there is one term with quadratic effect (Blue

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Radar's Detection Range). Finally, the Speed of the UAV seems to affect the response variable significantly. Thus, all three regression models are consistent in terms of which are the most influential predictors.

Table 21.   Sorted parameter estimates for the second order model ("Open Sea").

Sorted Parameter Estimates					
Term	Estimate	Std Error	t Ratio		Prob>|t|
Radar_MaxDetRange	4.5709e-6	3.524e-7	12.97		<.0001*
BlueShips_MaxDetRange	8.9803e-6	7.048e-7	12.74		<.0001*
UAV_MaxDetRange	5.4885e-6	5.64e-7	9.73		<.0001*
OpsCentre_CommsAccuracy	0.0021807	0.000282	7.74		<.0001*
Radar_AvgTimeBweenDet	-0.000569	0.000123	-4.64		<.0001*
MerchVessels_Speed	0.0048326	0.001167	4.14		<.0001*
NumberMerchVessels	-0.002233	0.000541	-4.13		<.0001*
(Radar_MaxDetRange-30000.2)*(Radar_MaxDetRange-30000.2)	-1.31e-10	3.39e-11	-3.88		0.0002*
Red_Stealth	-0.000872	0.000235	-3.71		0.0003*
UAV_AvgTimeBweenDet	-0.000423	0.000123	-3.45		0.0008*
BlueShips_AvgTimeBweenDet	-0.000196	6.076e-5	-3.23		0.0016*
Red_Speed	-0.001975	0.000703	-2.81		0.0058*
UAV_Speed	0.0004722	0.000176	2.68		0.0085*

b.   *Partition Tree*

Next, partition trees were created to more easily understand the regression results above. Partition Trees can be easily built using JMP. They are flexible because the user can go back and forth by "splitting" or "pruning" them. They are also able to handle both numeric and categorical data. Their main characteristic is their ability at fitting jumps or plateaus in the data, which provides the analyst with an easy-to-understand output.

To construct the Partition Tree we used the mean values of the MOE1 as the response variable and all the factors as input. The first seven splits occur on factors that were found to be the most important during the Regression Analysis, such as the Detection Ranges of all the Blue Sensors, as well as the Radar's Average Time between Detections. The exception to this is the speed of the Red Ships, which emerges as significant. The Partition Tree after the first seven splits (R^2= 0.667) is shown in Figure 45. We observe that the surveillance system performs better (Mean=0.43, SD=0.054) when the maximum detection ranges of the Blue Radar, ships and UAV are more than 22,188, 15,156 and

19,258 meters, respectively, and the speed of the Red Ships is less than 21 kn. In contrast, the surveillance system performs worse (Mean=0.077, SD=0.03) when the corresponding ranges are less than 22,188, 16,406 and 15,938 meters.
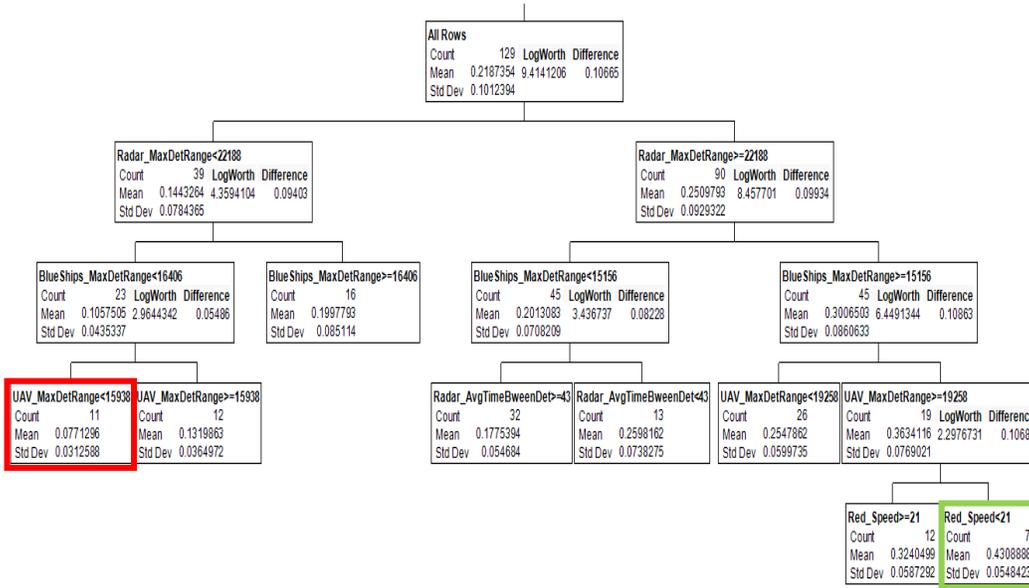

Figure 45. Partition tree for the "Open Sea" model after seven splits

Following that we created a Partition Tree with 21 splits, which gave R^2 0.856. The values of R^2 with respect to the number of splits are shown in Figure 46.
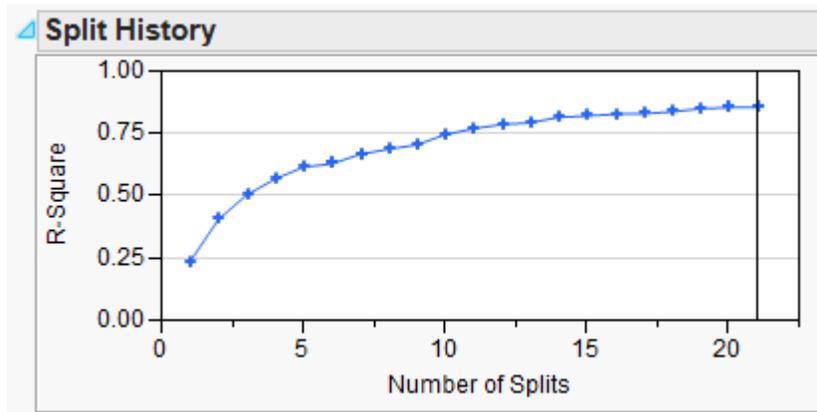
Figure 46. Split history for the Partition tree of the "Open Sea" model.

After sorting the variables that contribute to the response variable, we get the result of Table 22. Eight out of the ten significant factors that were found after fitting the model with the main effects are also indicated by the Partition Tree. It is worth noticing that just the Detection Ranges of the Blue Sensors explain about 78 percent of the MOE variability.

Table 22.   Variable contribution for the Partition tree of the "Open Sea" model.

Term	Number of Splits	SS	
Radar_MaxDetRange	2	0.32560017	
BlueShips_MaxDetRange	2	0.30547547	
UAV_MaxDetRange	4	0.22704193	
Radar_AvgTimeBweenDet	3	0.08647983	
Red_Speed	1	0.05046437	
BlueShips_Speed	1	0.03202279	
Red_Stealth	1	0.02894743	
UAV_AvgTimeBweenDet	1	0.02296974	
UAV_ProbClass	2	0.01281549	
BlueShips_PrClass	1	0.00899291	
NumberMerchVessels	1	0.00993990	
MerchVessels_Speed	1	0.00978825	
OpCentre_CommsLatency	1	0.00230404	
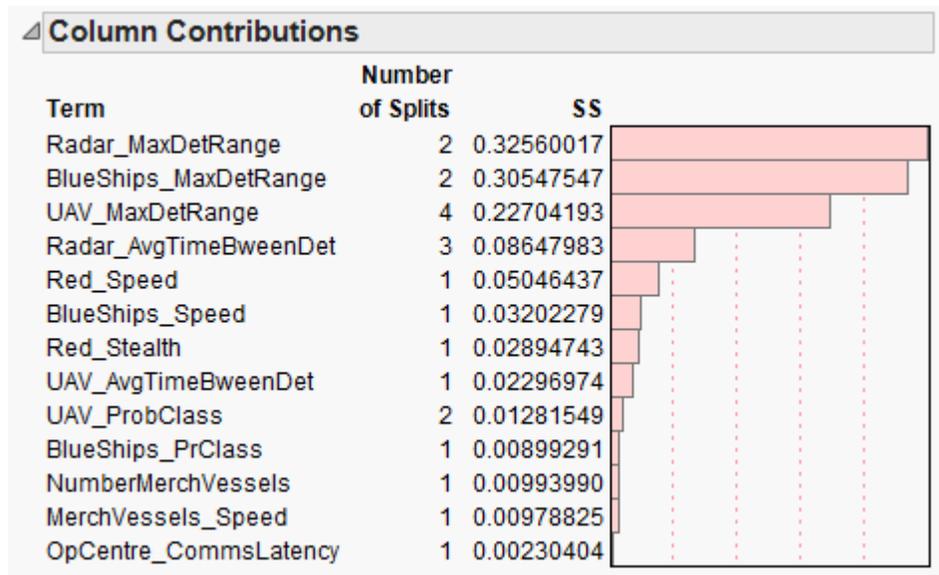
2.   "Many Islands" Model

The "Many Islands" model with one UAV (and specifically the northern one), which was created in MANA, used the appropriate DOE that was presented in Chapter V. The 129 DP were replicated 500 times, each resulting in 65,000 observations. Instead of using the raw data, we use the mean values of the replicated DP to reduce the calculations and produce more visually efficient displays.

a.   *Regression Analysis*

(1)   Main Effects Model. First we fitted a model with only the main effects of all the factors. Using the stepwise strategy and setting an alpha level of 0.01, we came to a model with only eight terms. We conducted model diagnostics and we noticed that all the model assumptions are met. The Residual by Predicted plot shows constant variance, and the Residual by Raw plot along with the large Durbin-Watson p-value (0.589) proves the independence of the observations. Finally, the Normal Quantile plot shows the Normality of the errors (Figure 47).
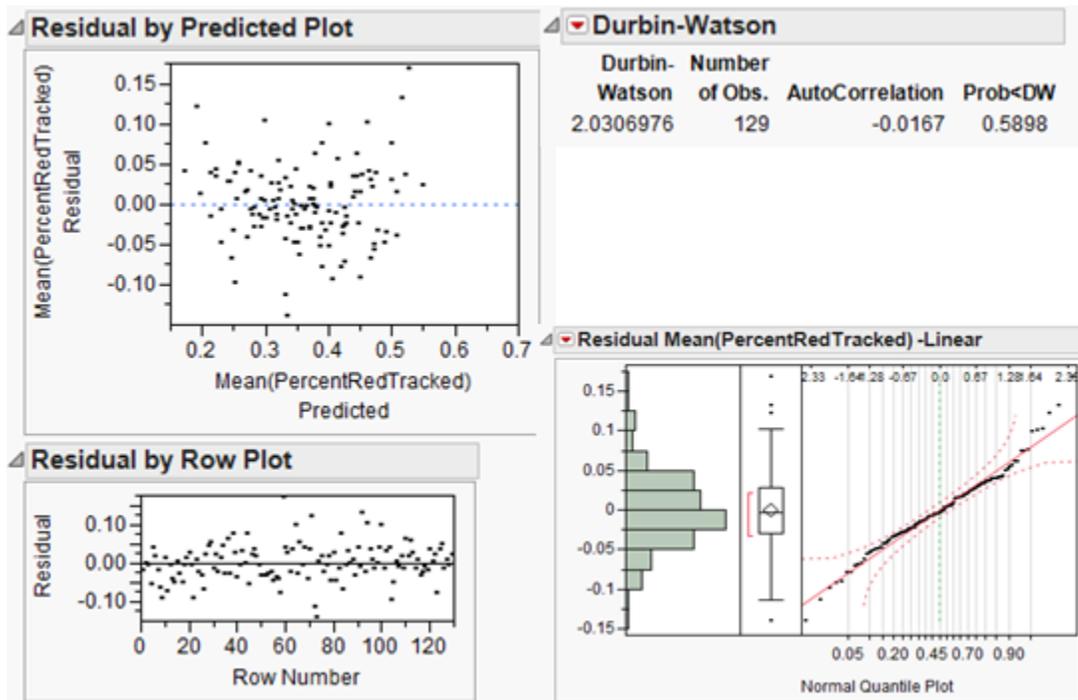

Figure 47. Model diagnostics for the main effects model ("Many Islands").

The model we ended up with involves eight factors and gives an *Adjusted* R^2 value of 0.742 (Table 23). The small p-value (<0.001) indicates that at least one of the predictors included in the model has great impact on the response.

Table 23.   Statistical results for the main effects model ("Many Islands").

Response Mean(PercentRedTracked)

Summary of Fit

RSquare	0.758305
RSquare Adj	0.742192
Root Mean Square Error	0.049536
Mean of Response	0.359977
Observations (or Sum Wgts)	129

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	8	0.9238422	0.115480	47.0616
Error	120	0.2944571	0.002454	Prob > F
C. Total	128	1.2182993		<.0001*

        The factors of the model were sorted in order of significance from high to low (Table 24). The Communication Accuracy of the Operational Centre emerges as the most significant factor followed by the detection ranges of the Blue Sensors. The Stealth of the Red Ships comes next, followed by the Average Times between Detections of the three Blue Sensors. To give the direction of the impact of each predictor, as the Communication Accuracy and the Detection Ranges of the Blue Sensors increase, the more effective the surveillance system becomes. In contrast, as the Red Stealth and the Average Time between Detections decreases, the surveillance system becomes less effective.

Table 24.   Sorted parameter estimates for the main effects model ("Many Islands").

Sorted Parameter Estimates

Term	Estimate	Std Error	t Ratio		Prob>|t|
OpsCentre_CommsAccuracy	0.0033661	0.0003	11.23		<.0001*
BlueShips_MaxDetRange	6.9471e-6	7.496e-7	9.27		<.0001*
UAV_MaxDetectionRange	4.8265e-6	5.997e-7	8.05		<.0001*
Radar_MaxDetRange	2.2715e-6	3.748e-7	6.06		<.0001*
Red_Stealth	-0.001253	0.00025	-5.02		<.0001*
UAV_AvgTimeBweenDet	-0.000549	0.00013	-4.22		<.0001*
Radar_AvgTimeBweenDet	-0.000438	0.00013	-3.36		0.0010*
BlueShips_AvgTimeBweenDet	-0.000175	6.462e-5	-2.71		0.0076*

(2) Main Effects Model with Interactions. To achieve a better model, we added all the two-way interactions to the previous model. Again we conducted model diagnostics and the results are shown in Figure 48. It can be easily seen that all the model assumptions are met. The Residual by Predicted plot shows constant variance, and the Residual by Raw plot along with the large Durbin-Watson p-value (0.607) proves the independence of the observations. Finally, the Normal Quantile plot shows the Normality of the errors. No further transformation is needed.
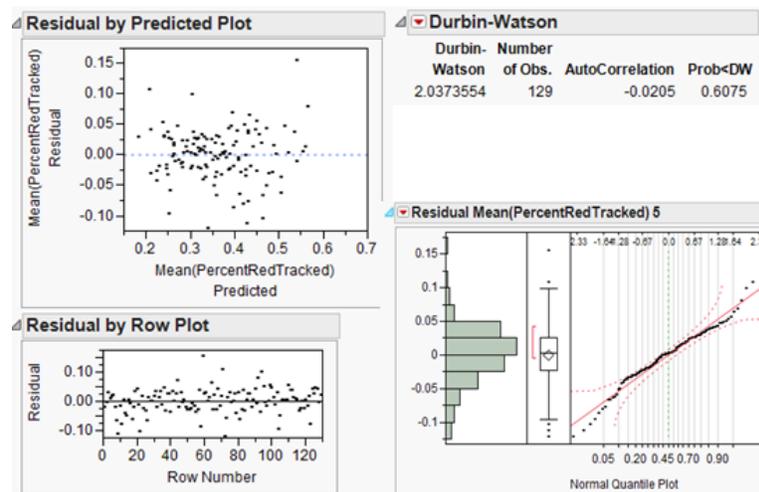
Figure 48. Model diagnostics for the main effects model with interactions ("Many Islands").

The new model contains ten factors and gives *Adjusted R^2* value of 0.798 (Table 25). The small p-value (<0.001) indicates that at least one of the predictors included in the model has great impact on the response.

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Table 25.   Statistical results for the main effects model with interactions ("Many Islands").

Response Mean(PercentRedTracked)

Summary of Fit

RSquare	0.814299
RSquare Adj	0.798562
Root Mean Square Error	0.043787
Mean of Response	0.359977
Observations (or Sum Wgts)	129

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	10	0.9920603	0.099206	51.7431
Error	118	0.2262390	0.001917	Prob > F
C. Total	128	1.2182993		<.0001*

The factors of the model with interactions were sorted in order of significance from high to low (Table 26). This model involves all the eight factors that the previous model had. In addition, the six most significant factors are exactly the same. Furthermore, this model suggests that the interactions between the Operational Centre's Communication Accuracy with UAV's Detection Range and the Stealth of the Red ships are also significant.

Table 26.   Sorted parameter estimates for the main effects model with interactions ("Many Islands").

Sorted Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
OpsCentre_CommsAccuracy	0.0033653	0.000265	12.70	<.0001*
BlueShips_MaxDetRange	6.947e-6	6.626e-7	10.48	<.0001*
UAV_MaxDetectionRange	4.8268e-6	5.301e-7	9.11	<.0001*
Radar_MaxDetRange	2.2708e-6	3.313e-7	6.85	<.0001*
Red_Stealth	-0.001255	0.000221	-5.69	<.0001*
UAV_AvgTimeBweenDet	-0.000549	0.000115	-4.77	<.0001*
(UAV_MaxDetectionRange-17500)*(OpsCentre_CommsAccuracy-75.0078)	1.6023e-7	3.499e-8	4.58	<.0001*
(OpsCentre_CommsAccuracy-75.0078)*(Red_Stealth-60.0155)	-0.000059	1.533e-5	-3.85	0.0002*
Radar_AvgTimeBweenDet	-0.000438	0.000115	-3.80	0.0002*
BlueShips_AvgTimeBweenDet	-0.000176	5.712e-5	-3.07	0.0026*
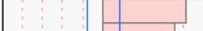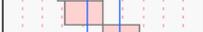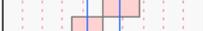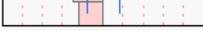
(3)   Model with Quadratic Effects. Finally, we fitted a polynomial model to check whether or not second order factors affect the MOE. Again, we conducted model diagnostics, and the results are shown in Figure 49. It can be easily seen that all the model assumptions are met. The Residual by Predicted plot shows constant variance, and the Residual by Raw plot along with the large Durbin-Watson p-value (0.357) proves the independence of the observations. Finally, the Normal Quantile plot shows the Normality of the errors. No further transformation is needed.
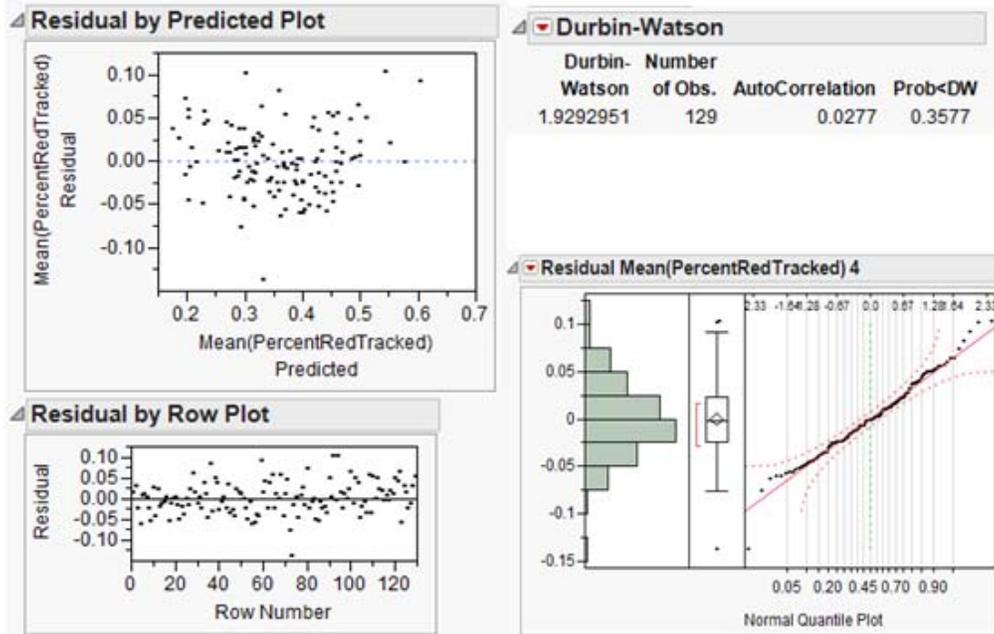
Figure 49. Model diagnostics for second order model ("Many Islands").

The last model contains 12 factors and gives *Adjusted R^2* value of 0.826 (Table 27). The small *p*-value (<0.001) indicates that at least one of the predictors included in the model has great impact on the response.

Table 27.   Statistical results for the second order model ("Many Islands").

The factors of the model with interactions were sorted in order of significance from high to low (Table 28). Comparing to the previous models, we notice that this contains all the main effects we observed previously, but instead of the interaction terms, it involves the quadratic effects of the Communication Accuracy of the Operational Centre, the Detection Range of the Blue Radar and the UAV, as well as the Time between detections of the UAV.

Table 28.   Sorted parameter estimates for the second order model ("Many Islands").

Sorted Parameter Estimates					
Term	Estimate	Std Error	t Ratio		Prob>|t|
OpsCentre_CommsAccuracy	0.003368	0.000246	13.68		<.0001*
BlueShips_MaxDetRange	6.9497e-6	6.157e-7	11.29		<.0001*
UAV_MaxDetectionRange	4.823e-6	4.926e-7	9.79		<.0001*
Radar_MaxDetRange	2.273e-6	3.079e-7	7.38		<.0001*
Red_Stealth	-0.001253	0.000205	-6.11		<.0001*
UAV_AvgTimeBweenDet	-0.000549	0.000107	-5.13		<.0001*
Radar_AvgTimeBweenDet	-0.000438	0.000107	-4.09		<.0001*
(OpsCentre_CommsAccuracy-75.0078)*(OpsCentre_CommsAccuracy-75.0078)	8.042e-5	0.00002	4.00		0.0001*
(Radar_MaxDetRange-30000.2)*(Radar_MaxDetRange-30000.2)	-1.12e-10	3.18e-11	-3.52		0.0006*
BlueShips_AvgTimeBweenDet	-0.000175	0.000053	-3.30		0.0013*
(UAV_AvgTimeBweenDet-62.5039)*(UAV_AvgTimeBweenDet-62.5039)	1.205e-5	3.661e-6	3.29		0.0013*
(UAV_MaxDetectionRange-17500)*(UAV_MaxDetectionRange-17500)	-2.03e-10	7.89e-11	-2.58		0.0112*

b.   *Partition Tree*

To construct the Partition Tree, we used the mean values of the MOE1, as the response variable, and all the factors as input. The first six splits occur on factors that found to be the most important during the Regression Analysis, such as the Communication Accuracy of the Operational Centre and Detection Ranges of all the Blue Sensors. The Partition Tree after the first six splits (R^2= 0.52) is shown in Figure 50. We observe that the surveillance system performs better (Mean=0.49, SD=0.07) when the Communication Accuracy of the Operational Centre is greater than 78 percent and the Blue Ships' Detection Range is more than 19,844 meters. In contrast, the surveillance system performs worse (Mean=0.25, SD=0.05) when the corresponding values are less than78 percent and 11,904 meters, respectively.
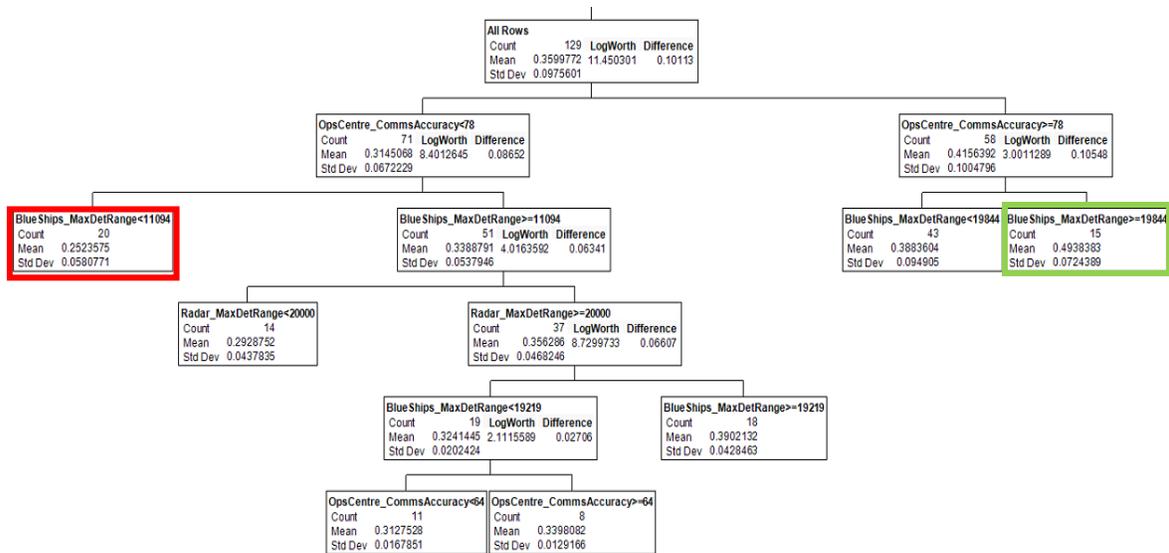
Figure 50. Partition tree for the "Many Islands" model after six splits.

Following that we created a Partition Tree with 20 splits which gave R^2 0.821. The values of R^2 with respect to the number of splits are shown in Figure 51.
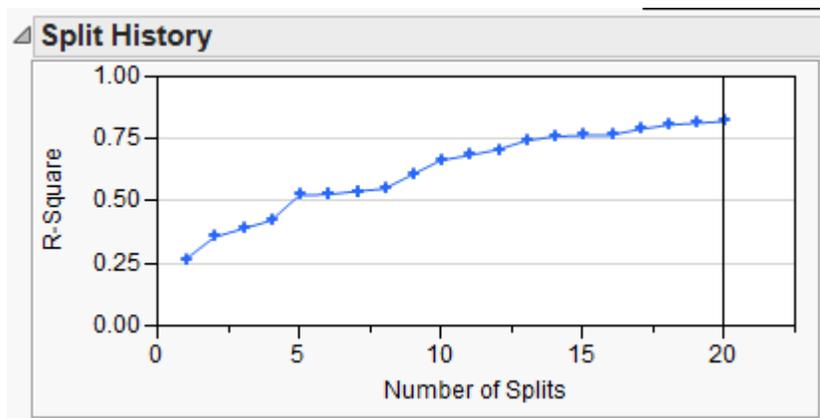
Figure 51. Split history for the Partition tree of the "Many Islands" model.

After sorting the variables that contribute to the response variable, we get the result of Table 29. It is worth noticing that the six most significant terms that the Partition Tree indicates explain about 94 percent of the MOE variability and were also predictors in the Regression Analysis.

Table 29.   Variable contribution for the Partition tree of the "Many Islands" model.

Column Contributions

| Term	Number of Splits	SS	
OpsCentre_CommsAccuracy	4	0.35727677	
BlueShips_MaxDetRange	4	0.31591995	
UAV_MaxDetectionRange	4	0.12535109	
UAV_AvgTimeBweenDet	1	0.06931791	
Radar_MaxDetRange	1	0.04084012	
Red_Stealth	1	0.02735960	
OpCentre_CommsLatency	1	0.02431740	
BlueShips_PrClass	1	0.02071166	
UAV_CommsLatency	1	0.00881418	
UAV_ProbClass	1	0.00864855	
Radar_ProbClass	1	0.00140383	
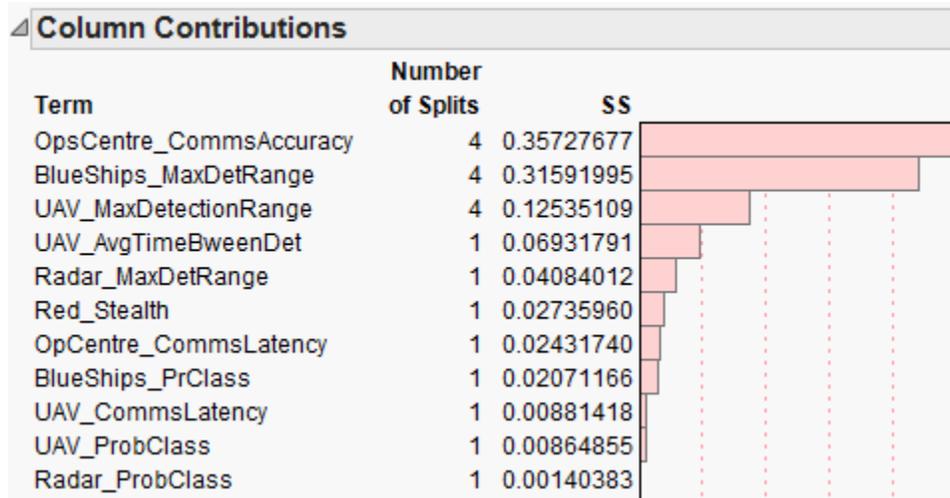
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VI. CONCLUSION

A. DISCUSSION AND OPERATIONAL INSIGHTS

1. Answers to the Primary Research Question

The hypothesis we tested was whether *"a surveillance system with UAVs performs better than one without UAVs assuming that the target's tactic is to approach transiting merchant vessels or to take advantage of nearby shorelines."* **This hypothesis was confirmed.** The simulation we created shows that integrating one or two UAVs into a traditional surveillance system makes it more efficient in the detection and persistent surveillance of enemies and neutral targets. This conclusion applies to all the areas of the Aegean Sea, either the Northern and Southern Aegean Sea (modeled by the "Open Sea" model), or the Central and Southeast (modeled by the "Many Islands" model).

In all the cases we studied, we found that a traditional system comprised only of surface ships and ground radars performs worse than a system that uses UAVs. Additionally, we explored a "futuristic" scenario where only two UAVs support the ground radars, without the use of surface ships (no Blue Ships scenario). The results showed that we can obtain similar results with this system as with the system in which we deploy one UAV and two surface ships in support of the ground radars (1-UAV scenario). This conclusion suggests that the decision makers should review the surveillance policy. They can shift to less reliance on the cost-ineffective use of surface ships towards the increased use of UAVs to better monitor maritime areas. This solution might be more feasible in adverse weather conditions and when there is lack of operational surface units available.

This study also demonstrated that the potential tactics the enemy might use to avoid detection cannot mislead UAVs. Regardless of whether the enemies try to take advantage of the nearby merchant vessels and sail close to them to transit long distances, or they use the shorelines of numerous islands as

coverage, a surveillance system that deploys UAVs has significantly better performance than a system that uses only ground radars and surface ships.

This thesis also shows that the area from where a UAV is launched affects the performance of the whole surveillance system. As it is easily understood, the more contacts there are close to the launch site, the more the UAV contributes to the surveillance system. That is, if the launch site is close to areas with high traffic, the UAV will have more opportunities to locate the targets. Additionally, the targets will be identified earlier. Therefore, it is extremely important to define the best launch site for the UAVs. From the literature review, we found that UAVs can be launched either from ground-based sites or appropriately equipped surface ships. Both solutions must be examined for strengths and vulnerabilities.

Furthermore, this study showed that the UAVs can mitigate a vulnerability that the ground radar systems inherently have: the incapability to cover their "blind sectors" that result from the way systems must be positioned. Because monitoring the whole range of the AOI with ground radars is not practical (it would require twice as many sensors), the existing radars are placed in areas with the most traffic. As a consequence, these systems are not always stationed at the highest point of an island, which results in a limited field of view. Additionally, taking into account that radar technology is subject to technical restrictions, the detecting capabilities are further narrowed. UAVs can easily cover those areas, providing information about existing targets.

Finally, it is worth noticing that the MOE in this study was the percentage of time the targets are positively identified. If another MOE had been set, i.e., the time until the first detection or classification, then the value of the use of UAVs is expected to be further recognized. Their speed and their potential larger detection ranges make them the most valuable assets compared to all the other traditional surveillance units.

2. Answers to the Exploratory Research Question

This thesis found the important factors that contribute to the maritime surveillance system. The two models, which simulated corresponding environments in terms of transiting merchant vessels, the existence of nearby islands and an enemy's tactics, were studied separately, but most of the input variables appear in both of them. These factors are described below.

- The detection range of all the sensors that are part of the surveillance system seems to have the most significant positive effect on the percentage of time the targets are classified. The partition tree for the "Open Sea" model highlights the importance of having the radars, the UAV and the ships detection ranges larger than 22, 19 and 16 km, respectively.

- Communication Accuracy of the Operational Centre has significant positive effect on the system's performance. The partition tree for the "Many Islands" model suggests if this factor has a value of at least 78 percent, it will have an ability to better monitor the area of interest. It is worth noticing that the Operational Centre is crucial in the communication network that we established because its role is to gather the information from each one of the sensors and send them to the patrolling units.

- Enemy's stealth is a factor that has significant negative impact on the percentage of time it is being classified. Enemy's stealth is presented in both the scenarios we studied where a target used a specific tactic to avoid being detected by the surveillance system. In reality, this factor describes the enemy's attempt to avoid the visual, IR and radar's contact using various methods.

- The number of merchant vessels and their speed has a negative effect on the surveillance system's performance only in the case in which the enemy tries to use them as a "Trojan Horse" to transit long distances. In environments where there is high traffic, either from merchant or fishing vessels, but the enemy does not try to take advantage of it, it seems that the surveillance system is not affected.

- Average Times between Detections of our own sensors are some more important factors in terms of the surveillance system's detection capability. All of them positively affect the percentage of time the targets are classified regardless the operational environment the system operates in.

- Enemy's speed is a factor that has a significant negative effect on the percentage of time the targets are classified. This factor

emerged only in the "Open Sea" model where the target has to transit long distances being "exposed" to adversary's surveillance system. This is operationally reasonable because when a target sails very close to the shoreline to avoid the detection, it cannot maintain a high speed due to navigation dangers.

- UAV speed has a positive effect on the system's performance only in the case where it has to cover large areas. This study showed that when the UAV had to cover areas with large number of islands, its speed was not important.

B.   FUTURE RESEARCH

This study was focused on the effectiveness of UAVs when integrated in a traditional surveillance system that monitors a complex maritime environment. By expanding the field of research or focusing on other key points, the following topics might be explored by future studies:

- The requirements for a surveillance system change significantly based on the situation in which it operates. Do we need it during peace time or war? How do things change if the UAV is capable of strike operations and/or it is subject to being hit by enemy targets? How vulnerable are the ground radars to attacks? If they are hit, how much of the whole system's performance is affected? A more war-focused scenario is believed to be able to provide insights to the aforementioned questions.

- This study explored two potential tactics that enemies could have used in a particular environment. They aimed to approach either large transiting merchant vessels or shorelines of the nearby islands. A combination of those, along with other enemy tactics, might be further explored.

- Given the complexity of the Aegean Sea and the number/type of assets assigned, a study could indicate the optimal placement of the ground radars. Additionally, should UAVs be launched from particular ground-based sites or from command ships that can be deployed wherever the demands are?

- A more detailed study could be done on the cost implications of the sensors that participate in the surveillance system. Is it cost-effective to use UAVs or surface ships? How many UAVs/ships/ground radars should be used? The financial problems and the budget constraints that most navies have to face make these questions more challenging.

C. TAKEAWAY

This thesis demonstrates that by integrating one or two UAVs into a traditional surveillance system, the system becomes more efficient in constantly detecting enemies or neutral targets regardless of the complexity of the maritime environment in which it operates. Additionally, the potential tactics the enemy surface ships might use to avoid detection cannot mislead UAVs. This study showed also that the area from where a UAV is launched affects the performance of the whole surveillance system; in particular, UAVs can mitigate the surveillance system's inability to cover its "blind sectors," which are inherent in ground radar systems. Finally, the most important factors that affect the surveillance system's performance in all the areas of Aegean Sea are the detection range of all the sensors, the communication accuracy of the Operational Centre, an enemy's stealth and the average times between detections of our own sensors. Moreover, in areas where the enemy has to transit long distances without the existence of many islands nearby, the number of merchant vessels and their speed, along with the enemy's speed and UAV speed, emerge as factors that have a significant effect on the percentage of time the targets are classified.

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APPENDIX A. COMPARISON BETWEEN NORTHERN AND SOUTHERN UAV FOR BOTH OPEN SEA AND MANY ISLANDS MODELS

In the following sections we provide a detailed comparison between the two different options when only one UAV is deployed. In the first scenario, the UAV is launched from a location in the Northwest, whereas in the second, the UAV started its deployment from the Southeast ("Open Sea" model) or the Southwest ("Many Islands" model), respectively. The information that follows involves boxplots, ANOVA and t-Test results. First, information for the "Open Sea" model is presented. In both the cases, statistical analysis shows that the location from which the UAV is launched does matter.

a. **"Open Sea" model.**

Oneway Analysis of %RedClassified By Case
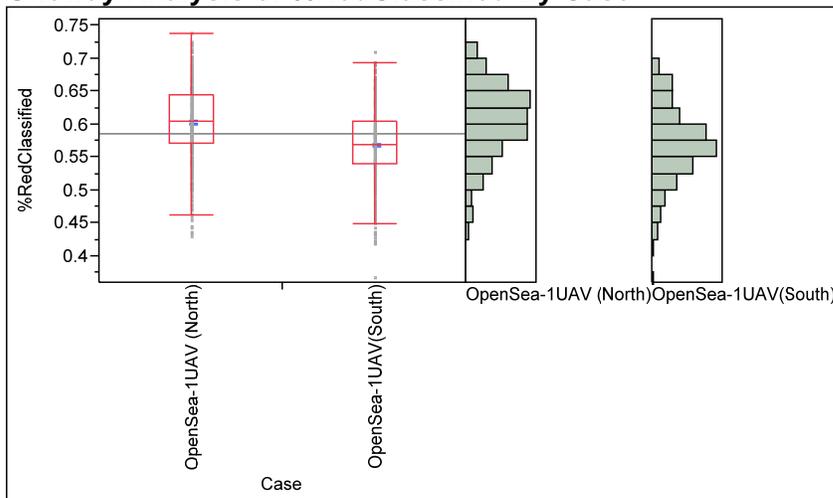
t Test
OpenSea-1UAV(South)-OpenSea-1UAV (North)
Assuming equal variances

Difference	-0.03376	t Ratio	-9.38131
Std Err Dif	0.00360	DF	998
Upper CL Dif	-0.02670	Prob > |t|	<.0001*
Lower CL Dif	-0.04082	Prob > t	1.0000
Confidence	0.95	Prob < t	<.0001*
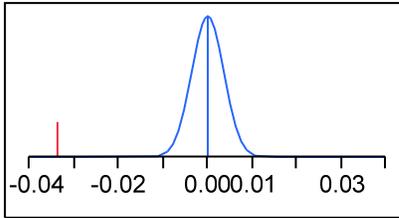
Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio	Prob > F
Case	1	0.2849663	0.284966	88.0090	<.0001*
Error	998	3.2314459	0.003238		
C. Total	999	3.5164122			

Means for Oneway Anova

Level	Number	Mean	Std Error	Lower 95%	Upper 95%
OpenSea-1UAV (North)	500	0.603269	0.00254	0.59828	0.60826
OpenSea-1UAV(South)	500	0.569507	0.00254	0.56451	0.57450

Std Error uses a pooled estimate of error variance

b.   "Many Islands" model

## Oneway Analysis of %RedClassified By Case
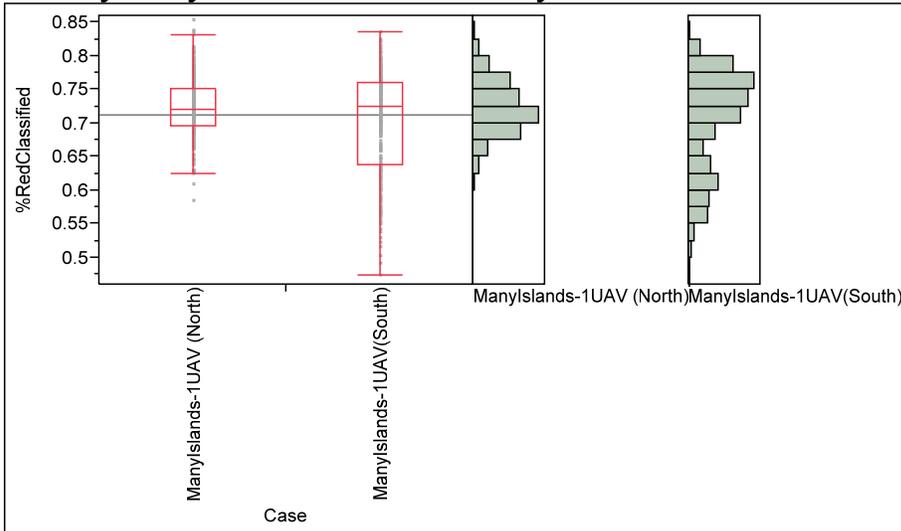
t Test

ManyIslands-1UAV(South)-ManyIslands-1UAV (North)
Assuming equal variances

Difference	-0.01981	t Ratio	-5.24457
Std Err Dif	0.00378	DF	998
Upper CL Dif	-0.01240	Prob > |t|	<.0001*
Lower CL Dif	-0.02723	Prob > t	1.0000
Confidence	0.95	Prob < t	<.0001*
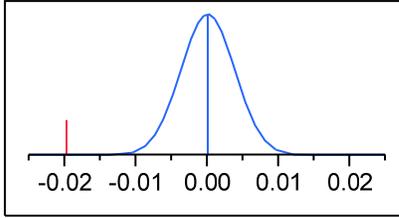
Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio	Prob > F
Case	1	0.0981541	0.098154	27.5055	<.0001*
Error	998	3.5613916	0.003569		
C. Total	999	3.6595457			

Means for Oneway Anova

Level	Number	Mean	Std Error	Lower 95%	Upper 95%
ManyIslands-1UAV (North)	500	0.722677	0.00267	0.71743	0.72792
ManyIslands-1UAV(South)	500	0.702862	0.00267	0.69762	0.70810

Std Error uses a pooled estimate of error variance.

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APPENDIX B. DIAGNOSTICS FOR PARAMETRIC ASSUMPTIONS OF MOE 2 IN OPEN SEA MODEL

Our decision whether to use a parametric or non-parametric method for the analysis is based on whether the assumptions of independence, equality of variance, and normality are met. Below we study those assumptions for the "Open Sea" model with respect to MOE 2. The boxplots and the Histogram of Residuals below show that the Equal Variance Assumption and the Near Normality Assumption, respectively, hold.
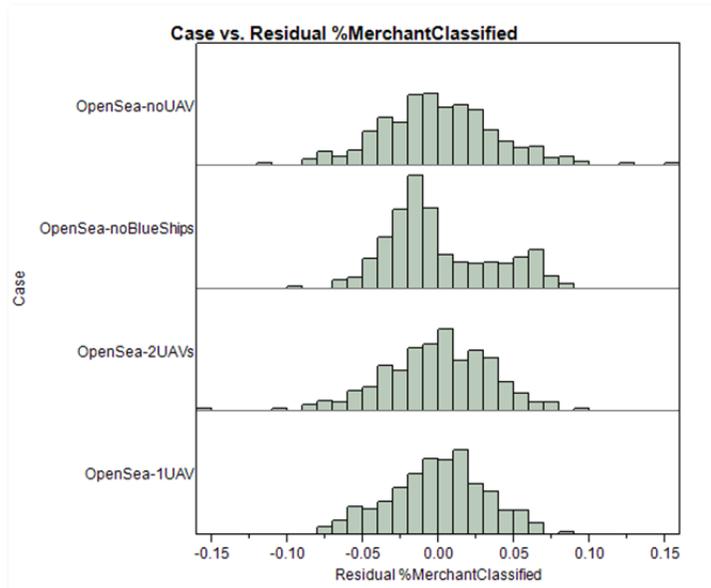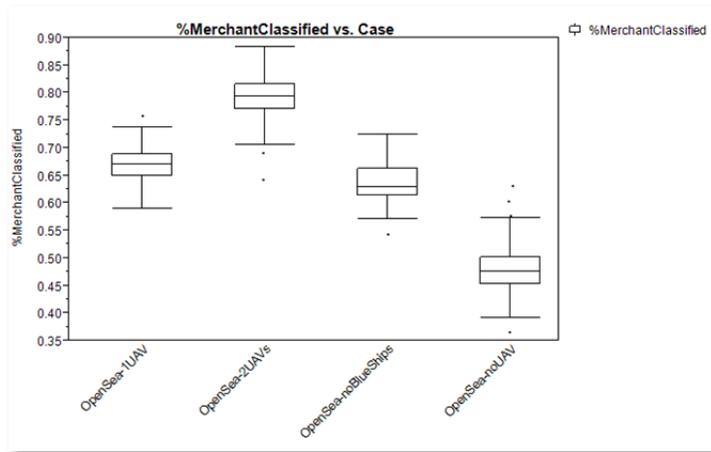
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APPENDIX C. DIAGNOSTICS FOR PARAMETRIC ASSUMPTIONS OF BOTH MOES IN MANY ISLANDS MODEL

In this appendix we provide the results of our study on whether the assumptions of independence, equality of variance, and normality are met. The results refer to both MOEs of the "Many Islands" model. First, the results about MOE1 are presented. The boxplots and the Histogram of Residuals that follow show that the Equal Variance Assumption and the Near Normality Assumption, respectively, hold.

   a. **MOE 1**
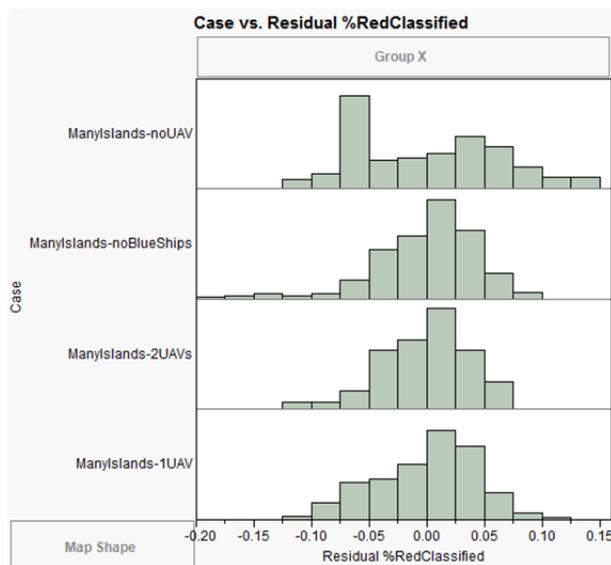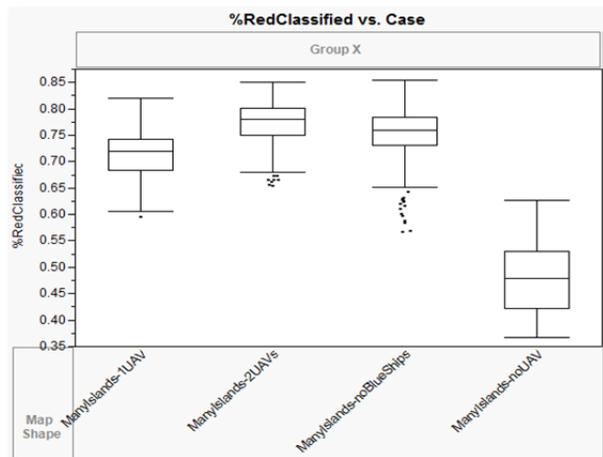
b. MOE 2
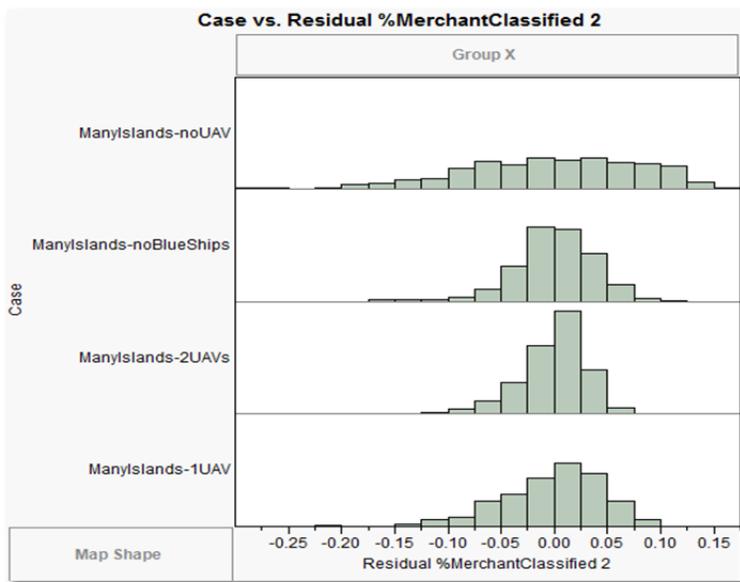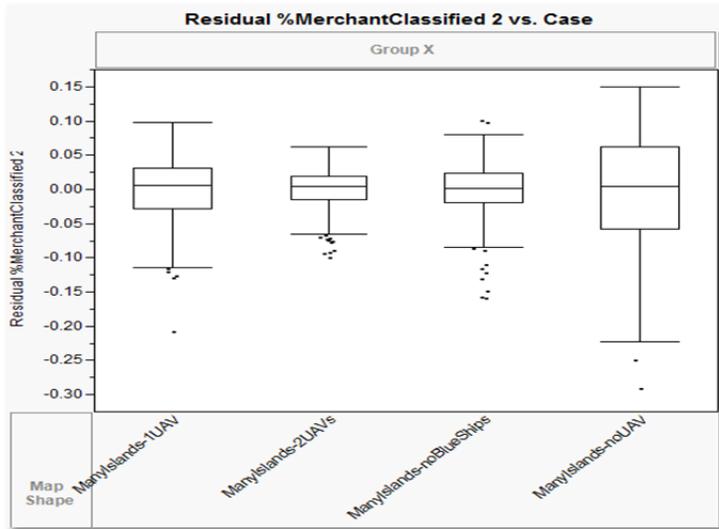
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